THREE ESSAYS ON INCOMPLETE CLIMATE POLICY IN A SECOND-BEST WORLD

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THREE ESSAYS ON INCOMPLETE CLIMATE POLICY IN A SECOND-BEST WORLD

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Policies to address climate change may not be optimal for several reasons. Policies may emerge through distortionary decisionmaking, reflecting disagreement among decisionmakers as to the extent that climate change should be addressed. Policies may be incomplete, i.e. only cover a subset of sectors or jurisdictions and thus be susceptible to carbon leakage, as unregulated agents respond to market forces by altering their emissions. Finally, policies may have unintended interactions with pre-existing regulations or other unpriced externalities which may far exceed the external benefits from reducing GHG emissions. Across three papers, this dissertation explores these aspects of U.S. climate policies.

Chapter 1 explores how disagreement among policymakers impacts federal and state efforts to address climate change and empirically examines which effort is likely to come closest to achieving an optimal climate policy. I find that federal policy results in a substantially greater scientific welfare gain than state policies with trading, of $14.3 billion and $3.7 billion, respectively, although neither policy is optimal.

In Chapter 2, Antonio M. Bento, Richard Klotz and I, link a multi-market economic model with an emissions model to quantify the importance of carbon leakage relative to the intended emissions savings resulting from the Renewable Fuel Standard (RFS) for conventional biofuels. The expansion of biofuels mandated by the RFS can increase or decrease emissions depending on the policy regime being evaluated with the most recent policy regime corresponding to a reduction in emissions of 2.0 $TgCO_2e$ in 2015.

Chapter 3 examines why policymakers frequently use a single policy instrument to address multiple market failures, as was the case for the RFS for conventional biofuels. Antonio M.

Bento and I perform a comprehensive welfare assessment of that policy, finding that the RFS consistently fails a benefit-cost test, with net costs totaling $1.6 billion in 2015. Each dollar reduction in the external costs of oil dependency comes at the expense of additional environmental external costs of $0.90. Our results suggest that policymakers may use a single instrument to address multiple market failures, less out of a regard for efficiency, but to increase the likelihood that a policy passes.

Biographical Sketch

Joel was born in Springfield, Illinois in 1981. Raised in Chatham, Illinois, he graduated from Glenwood High School there in 1999. Shortly thereafter, he began his undergraduate education at Warren Wilson College in Asheville, North Carolina, where he studied for a year before matriculating to Southern Illinois University in Carbondale. There he graduated *magna cum laude* in December of 2003 with two bachelor of arts degrees in Economics and Political Science (specializing in pre-law and international relations), and a minor in Philosophy. In 2004, he began his graduate education at the University of Maryland in College Park where he received a professional master's degree in public policy in the areas of development and environmental policy. In 2007, he was admitted to Cornell University in Ithaca, New York as a MS/Phd student in the Charles H. Dyson School of Applied Economics and Management. His primary field is environmental and energy economics, with additional interest in the fields of applied microeconomics, public finance, and political economy. His research focuses on climate change and renewable energy policy. In addition to receiving his PhD from Cornell, he also completes a graduate minor in computer science.

To my father, whose example has always been my greatest inspiration—

To my méméne, whose life has been and will forever be a bright light illuminating the way forward—

And to all those throughout my life, who saw potential in me, invested in me, and always demanded more from me than I ever thought possible—

May this effort serve as a reminder to always return the same.

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Chapter 1

How Disagreement Regarding Climate Change Affects Federal and State Efforts to Address It

1.1 Introduction

Most scientists and economists recognize that anthropogenic climate change requires immediate and consequential action, with one comprehensive study suggesting that climate change could lead to a loss to the United States equal to roughly 5% of US output.[1] Despite this, there remains widespread disagreement among decisionmakers as to whether policies to reduce greenhouse gas (GHG) emissions—the principal driver of climate change—should be enacted. Given this disagreement, which level of government should act is unclear.[2] In the US, various policies have been proposed at both the federal and state levels to address climate change. Disagreement over climate change interacts with the political and fiscal mechanisms which determine these policies, which need not be optimal. At the federal level, disagreement determines which legislative coalitions will form which may not reflect the preferences of all legislators. At the state level, disagreement leads 'believer' states to unilaterally reduce their emissions which may be undermined by 'skeptic' states who expand production and thus emissions.

The purpose of this paper is to understand how disagreement regarding climate change impacts the welfare implications of federal and state efforts to address it. To this end, this paper poses three related questions. How does disagreement over climate change affect the climate policies selected by federal and state governments? Secondly, which level of government should act to address climate change? That is, will state efforts to reduce emissions result in greater or less welfare than federal efforts? Third, how do the distributional conse-

[1] This corresponds to a warming of 11 °F by 2100 and includes estimates of nonmarket damages as well as costs arising from possible catastrophic outcomes (Nordhaus and Boyer (2000) and CBO (2009)).

[2] Under the assumption that decisionmakers seek or are able to maximize the welfare of the constituents within their respective jurisdictions, Wallace E. Oates (1972) seminal work on "fiscal federalism" suggests two divergent answers to the question of which level of government should act: federal decisionmaking may be preferred when cross-border spillovers from unilateral state action are large as federal decisionmaking may be able to internalize those spillovers, or state decisionmaking may be preferred when there is great disagreement or heterogeneity in preferences between states as state governments may be better suited to tailor local policies to satisfy local needs. With respect to climate change, Oates (1972) does not provide a clear path forward since spillovers are absolute given that GHG emissions are a global pollutant, *and* there is significant disagreement between states regarding climate change.

quences of federal and state decisionmaking differ?

To empirically answer these questions I develop a spatially and sectorally disaggregated equilibrium model of the US economy in which emissions are generated. I then link this economic model to models of federal and state decisionmaking that explicitly account for the role of disagreement over climate change on policy formation. To evaluate federal decisionmaking, I develop a legislative bargaining model (Baron and Ferejohn, 1989) that explains the structure of the caps and permit allocations observed under the American Clean Energy and Security Act (ACESA) of 2009, the only federal climate policy to have passed at least a single chamber of the US Congress. In this model, a proposing legislator simultaneously selects an emissions cap and an allocation of free permits to various sectors, where the total value of free permits, or green pork, is jointly determined along with the cap level.[3] To evaluate state decisionaking, I develop a model of horizontal competition (Zodrow and Mieszkowski, 1986) in state emissions caps, that attempts to explain why some 'believer' states unilaterally adopt climate policies such as Renewable Portfolio Standards, as well as how 'skeptic' states may respond in equilibrium with emissions expanding policies.

I calibrate the economic model using multiple spatial datasets which account for heterogeneity between legislative districts and states across several important dimensions: emissions intensity, endowments, and sectoral composition. To recover the parameters which reflect disagreement between decisionmakers with respect to climate change, I fit my legislative bargaining model which explains federal legislators' votes for the cap and permit allocation selected by a proposer, to the observed House votes for ACESA and the cap and permit allocation for 2021 under ACESA, given Representative Henry Waxman is the proposer. Intuitively, these parameters reflect bounds on what a legislator's perceived or re-

[3]The joint provision of these two public good streams reflects the logic of the "double dividend" long recognized in the environmental economics literature, namely a Pigouvian policy such as an emissions tax or an emissions cap generates tax or permit revenue which itself has value to society and can be used, for example, to reduce pre-existing distortionary taxes or otherwise distributed back to economic agents in society (e.g. Bovenberg and Goulder (1996)). The legislative bargaining model I develop provides a mechanism that explains how this revenue is likely to be recycled which is co-determined with the overall level of emissions reductions.

vealed valuation for emissions would need to be in order to justify their observed vote. This allows me to parameterize the models of decisionmaking and identify endogenous policies. Critically, policy formation is driven by disagreement over climate change through these revealed bounds and need not reflect scientific estimates of external costs of GHG emissions. I compare these policies using two 'welfare' metrics. The *scientific welfare* metric reflects the efficiency costs of the policy less the change in external damages from GHG emissions using estimates of external damages taken from the scientific literature. This is complemented using a *revealed surplus* metric which reflects the efficiency costs of the policy less the change in legislators' revealed valuations for emissions.[4] I compare both federal and state policies to three counterfactuals: 1.) the business as usual equilibrium of no climate policy, 2.) the policy that maximizes national *scientific welfare*, and 3.) the policy that maximizes national *revealed surplus*.

I highlight four key findings from my analysis. First, federal policy results in substantially larger emissions reductions than either state policy, achieving emissions reductions of 1,142.7 $TgCO_2e$ relative to business as usual relative to 177.4 and 12.8 $TgCO_2e$ for state policy with and without trading and offsets, respectively. Federal policy is more stringent because the legislative coalition consists of those legislators who especially value emissions reductions as well as those who value free permits or green pork. In contrast, under state policy, the emissions reductions of believer states are undermined by emissions increases in skeptic states as a result of strategic leakage.

Second, federal policy results in a far larger scientific welfare gain than state policy, although neither is optimal from the perspective of the policy that maximizes scientific welfare. Federal policy achieves a gain of $14.3 billion relative to business as usual, whereas state policy with trading and offsets yields a gain of $3.7 and state policy without trading and offsets a loss of $1.0 billion. Relative to the scientific welfare maximizing policy, federal

[4]While the scientific welfare metric reflects a conventional welfare assessment which is conditional on the selected scientific estimate of external damages, the revealed surplus metric reflects a positive analysis that is agnostic as to what legislators' value when setting climate policy or whether those valuations are justified, but which may not be a valid *welfare* metric.

policy leaves \$0.1 billion of additional welfare gains on the table, whereas state policy with trading and offsets leaves \$10.6 billion on the table. This result hinges upon the central scientific estimate of external damages that I assume (\$25.00 per ton CO_2e), with different welfare orderings under other preferred valuations.

Third, in sharp contrast to the first result, state policies result in a far smaller revealed surplus loss than federal policy, with losses of \$7.4 and \$ 1.7 billion for state policy with and without trading and offsets, respectively, compared to a loss of \$57.2 billion under federal policy. This emerges because federal policy achieves greater emissions reductions than state policies and because legislators' revealed valuations for emissions are on average -\$0.09 per ton CO_2e, reflecting significant skepticism with respect to climate change among decisionmakers in the US.

Fourth, the way in which permits were allocated under ACESA has very important implications both for the likelihood of federal policy passing as well as the stringency of the cap that emerges. Under ACESA, the imperfect targeting of permits to certain sectors in which fence-sitting yes voting legislators had high exposures demonstrates how green pork is essential to grease the wheels of climate policy. If permits were instead perfectly targeted to legislators directly, the scientific welfare gains from federal policy would fall by 88.9% or \$12.7 billion, relative to the the federal policy that results given the imperfect targeting that occurred under ACESA. While imperfect targeting under ACESA undershot the scientific welfare maximizing emissions level by 113.3 $TgCO_2$e, if permits could be perfectly targeted, federal policy would overshoot instead by 723.2 $TgCO_2$e. More precise targeting of permits increases the returns from hijacking as the proposer is able to extract more green pork for each additional reduction in emissions, but in this case results in overeating. As a consequence, imperfect targeting may actually be preferred to a perfect targeting mechanism for allocating permits, although greater targeting also likely increases the probability of a policy passing.

This paper proceeds as follows. Section 1.2 summarizes the literature to which this paper contributes. Section 1.3 provides an overview of ACESA. Section 1.4 introduces the model of the economy, the models of federal and state decisionmaking, and the alternative policy regimes for comparison. Section 1.5 discusses model calibration, including how I use my empirical framework to recover legislators' revealed valuations for emissions. Section 1.6 presents the full numerical results and resulting analysis. Finally, Section 1.7 provides caveats and concludes.

1.2 Review of the Literature

This paper contributes to two literatures. First, this paper contributes to a sizeable literature on "fiscal federalism" that was pioneered by Wallace E. Oates in 1972 and which seeks to understand when centralized and decentralized decisionmaking is likely to be preferred.[5] Most empirical efforts in this area have focused on econometrically testing certain model predictions using reduced form models, typically focusing on either decentralized or centralized decisionmaking.[6] To my knowledge, Banzhaf and Chupp (2012) is the only other attempt to use calibrated simulation models to empirically evaluate the welfare benefits of federal and state level decisionmaking with respect to environmental policy, although the context they examine is policies to address ambient air pollution generated by the electricity sector. This work differs from theirs in two important respects. First, my models of state and federal decisionmaking were chosen to capture realistic aspects of past efforts to address climate change and allow for the possibility for distortionary decisionmaking to result whereas Banzhaf and Chupp (2012) consider optimal decisionmaking. Second, Banzhaf and Chupp (2012), assume that decisionmakers internalize scientific estimates of the external damages

[5]For a review of the fiscal federalism literature see Oates (2005, 2008) and for the related 'environmental federalism' literature see Oates (2002) and Dijkstra and Fredriksson (2010). Finally, a closely related literature examines the welfare implications of political failure; see Battaglini and Coate (2007), for some useful references.

[6]Most recently, Boskovic (2013) evaluates whether decentralization under the US Clean Air Act of 1970 led to unintended emissions spillovers, finding evidence that sizable spillovers did emerge. Outside the context of environmental policy, a few papers have used calibrated simulation models to provide empirical estimates of the welfare impacts of decentralized fiscal competition (Parry, 2003; Wildasin, 1989; Sorensen, 2000, 2004). With respect to federal decisionmaking, Azzimonti et al. (2010) develop a calibrated dynamic model of legislative bargaining in the US that reflects the distortionary implications of deficit spending, and Merlo (1997) and Merlo and Tang (2012) have estimated stochastic legislative bargaining models to explain delays in coalition formation.

of ambient air pollution when setting policy. In contrast, I exploit the ACESA vote and the observed ACESA cap and permit allocation for 2021 to infer what legislators' revealed valuation for emissions would need to be to justify their vote. These valuations determine endogenous policies and thus need not reflect that all decisionmakers internalize scientific estimates of external costs when setting policies.

Second, my work contributes to the legislative bargaining literature. The bargaining model I develop differs from previous work in two ways. First, the joint determination of the cap and permit allocation explicitly links expansions in the global public good (emissions reductions) with expansions in the amount of local public goods (green pork) available for distribution. This differs from prior work that examined the provision of purely local public goods (e.g. Baron and Ferejohn, 1989; Knight, 2005; Merlo and Tang, 2012), the provision of local public goods with varying degrees of cross-border spillovers (Besley and Coate, 2003), or the provision of purely local public goods *or* a global public good (e.g. Volden and Wiseman, 2007 and 2008; Battaglini and Coate, 2007). In contrast, in my model legislators have two reasons for supporting a cap: they value emissions reductions, and/or they value the green pork generated from reducing emissions. As a result, the *ex post* coalition that forms in my model will almost always consist of members that highly value emissions reductions since they will require less green pork to secure their vote, and even if a proposer is a skeptic they may still propose a stringent cap since they still value pork. This reflects the ability for the cap to be 'hijacked'—set stringently, not because of the external benefits from reducing emissions, but because of the desire to increase the value of free permits and sequester those permits to one's district.[7] Because of this the amount of the global public good provided (emissions reduced) is more likely to be excessive both *ex post* and *ex ante* relative to the policy that maximizes national aggregate surplus. Second, in my model green pork cannot be directly allocated to districts, but instead are allocated to sectors and then to districts given their exposure to those sectors.[8] This inability to perfectly target permits to legislators

[7]This is in addition to the more conventional majoritarian bias discussed in Fredrikkson et al. (2010).

[8]This is similar in spirit to Knight (2005) in that the ability for the proposer to perfectly target yes voters

to secure votes limits proposer power and reduces the distortion caused by hijacking.

1.3 The American Clean Energy and Security Act of 2009

HR 2454, the American Clean Energy and Security Act of 2009 (ACESA)—more commonly known as the 'Waxman-Markey' climate bill because of its proposers Rep. Henry Waxman (D–California) and Rep. Ed Markey (D–Massachusetts)—was the first and so far the only federal climate bill to pass at least a single chamber of Congress, the US House of Representatives on June 26th, 2009. [9] The vote for ACESA of 219 to 212 was tight and largely fell on party lines with 211 Democrats joining 8 Republicans in voting yes and 169 Republicans joining 43 Democrats in voting against.

ACESA is a cap and trade policy consisting of two main components. First, ACESA sets national caps on emissions for each year between 2012 and 2050, covering 84% of all emissions produced in the United States by 2050. Second, each annual cap provides a pool of emissions permits. This pool of "green pork" was largely allocated freely to various sectors such as electricity generators and low-income consumers. Table 1.1 reports the caps and division of each cap as free permits across sectors for select years. Until 2025, roughly 99% of the cap was to be freely allocated. This declines each year between 2026 and 2050 with only about 46% of allowances freely distributed by 2050.[10]

is restricted, although the mechanism differs in my model. Here a proposer is allowed to jointly select a cap and an allocation of the cap to various sectors, such as oil refineries. Permits are then distributed to districts conditional on their exposure to those sectors. Fence-sitting legislators (moderates who vote for ACESA) may request a slice of permits to assist the industry which is most vulnerable in their district. Since fence-sitters have sectoral exposures that are similar to those of no voters, substantial permits may be allocated to no voters.

[9]Previous attempts to address climate legislation took place through the Senate (e.g. the Clean Air Planning Act of 2003, the Climate Stewardship and Innovation Act of 2007, the Low Carbon Economy Act of 2007, and the Lieberman-Warner Climate Security Act of 2008), with all attempts ultimately failing to come up for a vote. Serious discussions to address climate change under Barack Obama's presidency, on the other hand, began in the Democratic controlled House of Representatives. The desire to move climate legislation forward in the House was partially predicated on the existence of a simple majority threshold required there as opposed to the Senate, which according to procedural rules effectively requires a supermajority of 60% of its members.

[10]These percentages included permits directly allocated to sectors as well as permits auctioned off on their behalf. The remainder was to be auctioned off by the government with proceeds used to finance deficit reduction and/or a Climate Change Consumer Refund (Environmental Protection Agency, 2009).

Both the caps and these permit shares were negotiated jointly as ACESA made its way to the House floor. Starting in the House Energy and Commerce Committee in May 2009, critical early negotiations occurred with a bloc of moderate Democratic representatives in industrial districts led by Representative Rick Boucher (D–Virginia), an ally of the coal industry and whose own district was heavily dependent on coal for electricity generation purposes (Holly, 2009). Several important concessions were made in this first round of negotiations. Waxman, the committee chairman, advocated a cap on 2020 emissions set 20% below 2005 levels. Boucher's starting offer was a 2020 cap that was 6% below 2005 levels, with final agreement attained on a reduction in emissions of 17% of 2005 levels by 2020. This 17% was higher than the 14% reduction proposed under President Obama's fiscal year 2010 budget (Holly, 2009).[11]

In exchange, Boucher secured allowances totaling 35% of the cap to the electricity industry, accounting for roughly 90% of the emissions from that sector.[12] Allowances equal to 9% of the cap would go to LDCs for natural gas, and a further 5% for carbon, capture and storage (CCS). As part of a deal worked out with Representative Mike Doyle (D–Pennsylvania) and other legislators from manufacturing districts, allowances comprising 15% of the cap would be allocated to vulnerable industries such as steel, aluminum, and chemical producers. To secure the support of Representative Gene Green (D–Texas), oil refiners were assured an additional 2% of the total allowance pool.[13] These allowances would continue at this level until 2025, gradually decline until 2030, at which point they would be fully eliminated (Holly, 2009). Given these negotiations ACESA passed the House Energy and Commerce Committee

[11] Although, Obama offered a lower reduction of 14% based on earlier efforts in this area, he also offered a 100% auction of permits, which industry groups opposed, largely because details on how auction proceeds would be distributed were never fully articulated and were assumed to consist of per-capita rebates to consumers (Pooley, 2010). The linkage between the stringency of the cap and the permit allocation has even been recognized in the popular press; as Eric Pooley notes, "Basically more allowances and offsets meant [coal-fired utilities] could agree to more aggressive 2020 reductions" (Pooley, 2010).

[12] This includes a carve-out of allowances equal to 5% of the cap to merchant coal generators, which was used to attract House members from Texas and the Midwest, who had a larger share of merchant coal-fired power plants (Behr, 2009).

[13] Green reportedly said: "I can't vote for a bill unless my refineries [are protected] because of the nature of my district, it's a job base and a tax base" (eNewsUSA, 2009).

by a vote of 33 to 25 on May 21st, 2009.

A second obstacle to securing passage in the House, emerged when Representative Collin Peterson (D–Minnesota), chairman of the House Agriculture Committee, threatened to send the bill to his committee for a full mark-up unless additional concessions were made on behalf of US agriculture. Peterson and a bloc of 45 legislators from the Midwest were brought on board after Waxman agreed to USDA oversight of offsets and other concessions. Finally, on the day ACESA went up for a full House vote, Waxman continued to cut deals on the floor until the bill passed, adding an additional 300 pages to its already considerable 1,200 pages (Tankersley, 2009).

1.4 Model

1.4.1 The Business as Usual Economy

Consider a model of the national economy consisting of $d = 1, ..., D$ districts and seven economic sectors: electricity, heating oil, petroleum refineries, automobiles, trade vulnerable industries, and ‘other economic’ which are $s = 1, ..., 7$, respectively. In the case of federal decisionmaking D is the number of legislative districts in the US House of Representatives, and in the case of state decisionmaking D is the number of state governments. Capital is mobile between districts whereas labor and all other goods are assumed to be immobile.

Consumption

A representative consumer in each district possesses a fixed labor endowment, $\bar{L}_d$, and elastically supplies capital, K_d, according to:

$$K_d(r) = \zeta_d^{-\eta} r^{\eta}, \tag{1.4.1}$$

where r is the rate of return to capital, ζ_d is a scaling parameter and η is the elasticity of capital supply.[14] Since capital is elastically supplied, I need to account for the cost of supplying capital which is defined as: $\kappa_d(r) = rK_d(r) - \int_0^r K_d(x)\,dx = \zeta_d^{-\eta}\left(\frac{\eta}{1+\eta}\right)\left(r^{(1+\eta)}\right)$.

The aggregate surplus of the representative consumer reflects the utility they receive from consuming a final good, x_d, and global emissions, E_0, less the cost of supplying capital and which is given by:

$$U_d(x_d, E_0, r) = x_d - \phi_d E_0 - \kappa_d(r), \tag{1.4.2}$$

where ϕ_d reflects the representative consumer's perceived marginal valuation for GHG emissions, which can be positive (climate 'believers') or negative (climate 'skeptics').[15]

The private budget constraint facing the consumer is given by: $x_d = \pi_d + rK_d$ where π_d is the net returns from producing the final good. Consumer's choose x_d to maximize (1.4.2) subject to this budget constraint. Emissions are exogenous to consumers and in the absence of government intervention they do not consider the impact of their choices on emissions. Likewise, consumers do not consider the impact of their choices on the rate of return to capital when making decisions and so κ_d is also exogenous. This provides the Walrasian demand for the final good which is given by: $x_d(r, \pi_d)$.

[14] Since I assume that capital is elastically supplied, and emissions are assumed to vary with the amount of intermediate capital used in production, total emissions in the economy will vary given the rate of return to capital. This is in contrast to Ogawa and Wildasin (2009).

[15] Given a few additional assumptions, the first two terms in (1.4.2), which reflects the utility to consumers in the district, can be understood in two ways: as a monotonic transformation of the utility of the median voter defined as $u_d = x_d - \phi_d E_0$, or as the sum of the utility of all consumers in the district. To see this, define the preferences of a consumer, $c(d)$, located in district d as: $u_{c(d)} = x_{c(d)} - \phi_{c(d)} E_0$, where $\phi_{c(d)}$ is assumed to be distributed given a symmetric discrete probability distribution function with median (mean) $\phi_{\mu(d)} = \frac{\phi_d}{n_d}$, n_d is the number of consumers who are all assumed to be voters, and $\phi_d = \sum_{c(d)}^{n_d} \phi_{c(d)}$. Then the preferences of the median voter is given by: $\frac{x_d}{n_d} - \phi_{\mu(d)} E_0$, where $x_d = \sum_{c(d)}^{n_d} x_{c(d)}$, which after multiplying across by n_d (a monotonic transformation), is simply the first two terms of (1.4.2). Alternately, the utilitarian sum of the preferences of all consumers is given by: $\sum_{c(d)}^{n_d} x_{c(d)} - \phi_{c(d)} E_0 = x_d - \phi_d E_0$.

Production

The final good is produced by a representative firm in each district according to the following constant returns-to-scale CES production function:

$$X_d(y_d, l_d) = \gamma_d \left(\rho_d y_d^\sigma + (1-\rho_d) l_d^\sigma\right)^{\left(\frac{1}{\sigma}\right)}, \tag{1.4.3}$$

where X_d is the amount of the private good supplied, y_d is the demand for a capital composite, and l_d is demand for labor. γ_d and ρ_d are the scaling and share parameters, respectively, and σ is the elasticity of substitution.

The capital composite is produced according to the following constant-returns-to-scale Leontief production function:[16]

$$y_d(k_d) = \min\left\{\frac{k_{ds}}{\omega_{ds}}\right\}_{s=1}^{S}, \tag{1.4.4}$$

where k_{ds} is the amount of sector s capital used to produce the capital composite, and ω_{ds} is a parameter specifying the amount of capital intermediate, k_{ds}, demanded per unit of y_d. Since y_d is a composite of capital and I wish to keep things in consistent units of capital throughout, I restrict $y_d = \sum_{s=1}^{s} k_{ds}$, which is the same as requiring that $\sum_{s=1}^{S} \omega_{ds} = 1$ since (1.4.4) implies that $k_{ds}(y_d) = \omega_{ds} y_d$.

Emissions are generated by each district, E_d, according to:

$$E_d(y_d) = \sum_{s=1}^{S} \alpha_s k_{ds} = \alpha_d y_d, \tag{1.4.5}$$

where $\alpha_s > 0$ is the amount of emissions produced per unit of k_{ds}, which differs across sectors but is assumed to be constant between districts. The alternate characterization on the right

[16]The Leontief specification allows me to greatly simplify the solution for the economic equilibrium which in this model is conditional on the models of decisionmaking, and so must be solved for repeatedly.

of (1.4.5), reflects that emissions will vary per unit of composite capital used in each district, given $\alpha_d = \sum_{s=1}^{S} \alpha_s \omega_{ds}$, and thus that some districts will be marginally dirtier producers than others. Finally, the total amount of emissions generated in the economy is simply: $E_0 \left(\{y_d\}_{d=1}^{D} \right) = \sum_d^D E_d \left(y_d \right)$.

Under the business as usual of no climate policy, the representative firm located in each district maximizes profits according to:

$$\begin{aligned} &\max_{y_d \geq 0, \{k_{ds}\}_{s=1}^{S} \geq 0} && \gamma_d \left(\rho_d y_d^{\sigma} + (1-\rho_d) \bar{L}_d^{\sigma} \right)^{\left(\frac{1}{\sigma}\right)} - r y_d \\ &\text{subject to:} && y_d = \min \left\{ \frac{k_{ds}}{\omega_{ds}} \right\}_{s=1}^{S}. \end{aligned} \tag{1.4.6}$$

where I have imposed market clearing in the local labor market, i.e. $l_d = \bar{L}_d$. Consequently, the unconditional demands for composite and intermediate capital are $y_d(r)$ and $k_{ds}(r)$, respectively. The amount of the private good supplied is $X_d(r)$ and total firm profits, $\pi_d(r)$, reflects the returns to the local labor endowment.

Equilibrium

Under the business as usual of no climate policy, the competitive equilibrium is the rate of return to capital, r, and the resulting economic outputs given maximization of (1.4.2) subject to the private budget constraint, (1.4.1), (1.4.6), and (1.4.5) such that the capital and private good markets clear:[17]

$$\begin{aligned} \sum_{d=1}^{D} K_d \left(r \right) &= \sum_{d=1}^{D} y_d \left(r \right), \\ \sum_{d=1}^{D} x_d \left(r, \pi_d(r) \right) &= \sum_{d=1}^{D} X_d \left(r \right). \end{aligned} \tag{1.4.7}$$

[17] According to Walras' Law, only one of these two equations need be satisfied.

1.4.2 Federal Decisionmaking

Federal climate policy is determined through a legislative bargaining model in the spirit of Baron and Ferejohn (1989) and Volden and Wiseman (2007, 2008).[18] This model captures the structure of ACESA by linking the choice of emissions cap to the free allocation of permits to sectors.[19] The joint determination of the cap with the allocation of permits through the legislative process is crucial in that it allows the cap to be *hijacked*—a marginally more stringent cap may be selected not necessarily because a proposing legislator marginally values the emissions reductions provided by the cap, but because of the greater marginal value of the free permits that the tighter cap provides. This increases the likelihood that both the *ex ante* and *ex post* federal decisionmaking equilibria will result in a cap that is more stringent than a cap that maximizes the national sum of legislators' revealed aggregate surplus (following (1.4.20) below).[20] Of course, allowing permits to be allocated through the political mechanism also increases the likelihood that the policy will pass, highlighting a fundamental trade-off between the possibility that a cap may be set too stringently and the likelihood that a cap will emerge at all.

[18] Fredrikkson et al. (2010) is also related to my effort here. They examine the role of majority bias in the choice of an emissions tax by a central government and show that when there is heterogeneity in incidence as well as heterogeneity in emissions spillovers between districts that a simple majority of legislators will select either a vector of district level taxes or a uniform tax that places a greater burden on those districts not in the majority. Their approach, however, assumes homogeneity in preferences for the environmental good, ignores the endogeneity of coalition formation in the presence of heterogeneity, and takes the allocation of tax revenue as exogenous. All of these assumptions are relaxed in the framework I develop here, and thus the majority bias I identify is likely to be even more distortionary.

[19] The joint determination of the cap and permit allocation is not a violation of the "independence property" between the cap and the allocation detailed by Hahn and Stavins (2011), but, rather, reflects the connectedness between the cap and permit allocation through the political mechanism; as they note: "The choice of an environmental goal and the choice of a particular policy instrument for achieving that goal may be connected, and similarly it is possible that the choice of the cap-and-trade system may be connected with the choice of a specific allocation."

[20] For a simpler version of the model in which some of the parameters are restricted, this intuition is demonstrated analytically in Section A.2.1 in the Appendix. There I also show how imperfect targeting (i.e. ACESA) reduces the capacity for hijacking relative to a bargaining model in which a proposing legislator can perfectly target permits to individual legislators. Finally, this intuition hinges upon the representative consumers' perceived marginal valuation for GHG emissions following (1.4.2). The resulting cap may or may not be too stringent relative to a scientific standard, which is why I also compare the results from decisionaking to a cap that maximizes welfare reflecting scientific estimates of external damages (see (1.4.19) below.)

A representative consumer located in each district sends a legislator to the national assembly with aggregate surplus equal to that of the representative consumer. The legislative process is represented as a one-shot noncooperative bargaining game. In the first-stage, a proposing legislator denoted by subscript p is randomly drawn (reflecting an equal recognition rule) from all D representatives to offer a federal climate policy consisting of a national cap on emissions, $\bar{E}_0$, as well as a vector of shares of the cap to be allocated to various sectors $\boldsymbol{\theta} = \{\theta_s\}_{s=1}^{\bar{S}}$, where sectors include both *economic sectors* which follow the model above and are subscripted $s = 1, ..., S$, as well as *civic sectors* which I denote as $s = S+1, ..., \bar{S}$.

In the second stage, all legislators vote on whether or not to accept the climate policy. A legislator votes for the climate policy ($v_d\left(\bar{E}_0, \boldsymbol{\theta}\right) = 1$) if its aggregate surplus under the climate policy equals or exceeds its aggregate surplus under no policy, that is if $U_d\left(\bar{E}_0, \boldsymbol{\theta}\right) \geq U_d^{BAU}$, where the superscript BAU reflects the solution to the economic model under the business as usual of no climate policy. If the reverse inequality holds then the legislator will vote against the policy ($v_d\left(\bar{E}_0, \boldsymbol{\theta}\right) = 0$). If at least a simple majority (D_M) of legislators votes in favor, i.e. if $\sum_{d=1}^{D} v_d\left(\bar{E}_0, \boldsymbol{\theta}\right) \geq D_M$, then the climate policy is implemented. Thus, the proposer solves:

$$\begin{aligned}
&\max_{\bar{E}_0, \boldsymbol{\theta}} && U_p\left(\bar{E}_0, \boldsymbol{\theta}\right) \\
&\text{subject to:} && \sum_{d=1}^{D} v_d\left(\bar{E}_0, \boldsymbol{\theta}\right) \geq D_M, \\
& && U_p\left(\bar{E}_0, \boldsymbol{\theta}\right) \geq U_p^{BAU}, \\
& && \sum_{s=1}^{\bar{S}} \theta_s \leq 1.
\end{aligned} \tag{1.4.8}$$

where $D_M = \frac{D+2}{2}$ ($D_M = \frac{D+1}{2}$) if D is even (odd). The first constraint in (1.4.8) reflects the majority voting requirement whereas the second constraint imposes that the proposer actually gain from setting a climate policy. Finally, the last constraint simply reflects the fact that the total number of permits freely allocated to all sectors must be less than or equal to the national cap.

Imperfect Targeting and the Allocation of Permits From Sectors to Districts

The proposer is not able to target permits directly to legislators through the legislative process, but instead is only allowed to determine the amount of permits going to each sector, $\theta_s \bar{E}_0$. Instead, a district's *exposure* to a given sector, δ_{ds}, determines the proportion of a given sectoral permit allocation that a district receives, $\delta_{ds}\theta_s\bar{E}_0$. Consequently, the number of permits going to each district, ξ_d, equals:

$$\xi_d = \sum_{s=1}^{\bar{S}} \delta_{ds}\theta_s\bar{E}_0, \tag{1.4.9}$$

where $\sum_{d=1}^{D} \delta_{ds} = 1$. For economic sectors, a district's exposure equals the proportion of capital demanded by that district for that sector to the total amount of capital demanded by that sector across all districts: $\delta_{ds}\left(\bar{E}_0, \boldsymbol{\theta}\right) = \left(\frac{k_{ds}\left(\bar{E}_0,\boldsymbol{\theta}\right)}{\sum_{d=1}^{D} k_{ds}\left(\bar{E}_0,\boldsymbol{\theta}\right)}\right)$. For example, the share of the oil refineries in one's district relative to those present nationally determines the amount of permits allocated to oil refineries that the district receives. These economic sectors follow the ACESA climate policy outlined in Table 1.1. In addition, I consider seven civic sectors which reflect the seven broad categories of permits otherwise distributed by ACESA. These include: low-income consumers, carbon capture and storage (CCS), renewables, adaptation, workers, buildings, and other civic which are $s = 8, ..., 14$, respectively. Exposure to civic sectors reflects the exogenous characteristics of districts. For example, exposure to 'low-income consumers' reflects the proportion of low-income individuals located in a particular district to the total number of low-income individuals nationally.

The proposer's inability to directly target permits to districts, i.e. the proposer chooses θ_s and not ξ_d, reflects *imperfect targeting.* Imperfect targeting captures important empirical realities that a model with perfect targeting (i.e. the classical models of Baron and Ferejohn (1989), Volden and Wiseman (2007, 2008)) would not permit. Similar realities persist in other contexts in which legislative bargaining models have been applied to observed votes, such as the allocation of the Highway Trust Fund in which even no voting legislators receive a positive allocation of the fund (Knight, 2005).[21] In the model here, imperfect targeting weakens the ability of the proposer to funnel residual distributional benefits (those remaining after a majority coalition has been bought out) to their own district and thus constrains hijacking. Put in terms of the literature in this area, imperfect targeting reduces proposer power (Knight, 2005). Imperfect targeting implies that a proposer is forced to use a blunt instrument to assign the green pork necessary to to get his/her bill passed. This raises the costs to building a legislative majority and diminishes the space in which the proposer is able to get a bill passed, but also ensures some equity by providing a mechanism for no voters to also receive permits. The determinants of imprecision may reflect a desire to obscure blatant pork barrel spending from constituents, to limit gross inequality, or to avoid future repeal should legislators one day find themselves in the minority instead of the majority (Diermeier and Fong, 2011).

The Economy Under Federal Climate Policy

Under ACESA, offsets can be purchased either internationally or domestically, according to the following national supply functions:

$$\begin{aligned} A^I(P) &= (\zeta^I)^{-\eta^I} P^{\eta^I}, \\ A^H(P) &= (\zeta^H)^{-\eta^H} P^{\eta^H}, \end{aligned} \tag{1.4.10}$$

[21]In Knight's model a non-majoritarian gate-keeping committee decides how to split a fixed budget (the Highway Trust Fund surplus) into two, a portion that is equally divided to everyone in the gate-keeping committee and another portion that is equally divided to everyone else. Since the gatekeeping committee lacks a majority on its own, it must allocate some portion of funds to those outside of the committee such that the policy passes under a majority vote. Since permits allocated outside of the committee cannot be targeted, super-majoritarian committees are not uncommon, which reflects historical legislative votes in the area Knight examines. This model is not well suited to the context of climate policy, however. While the Highway Trust Fund is consistently allocated by the House Committee on Transportation and Infrastructure, major policy initiatives, such as climate change policies like ACESA, can originate from several committees, and once leaving the originating committee may still be held up by other committees. As Section 1.3 shows this in fact occurred in the negotiations over ACESA.

where P is the price of permits/offets, ζ^I and ζ^H are scaling parameters and η^I and η^H are the elasticities of international and domestic offset supply.[22] Under ACESA, international offsets account for four-fifths of domestic abatement and so total offsets supply is given by: $A(P) = 0.8A^I(P) + A^H(P)$.

When offsets are accounted for, aggregate surplus as reported in (1.4.2) is instead:

$$U_d(x_d, E_0, r, P) = x_d - \phi_d E_0 - \kappa_d(r) - \kappa_d^H(P), \tag{1.4.11}$$

where $\kappa_d^H = \lambda_d \left(\frac{\eta^H}{1+\eta^H}\right)(\zeta^H)^{-\eta^H} P^{1+\eta^H}$ is the cost of supplying domestic offsets and λ_d is the share of domestic offsets supplied by the district. Likewise, the private budget constraint is now: $x_d = \pi_d + rK_d + P\lambda_d A^H$.[23] Maximization of aggregate surplus subject to the private budget constraint provides the Walrasian demand for the private good which is given by $x_d(r, P, \pi_d)$.

Given (1.4.3) and (1.4.4), under the federal climate policy, the representative firm instead solves:

$$\begin{aligned}
\max_{y_d \geq 0, \{k_{ds}\}_{s=1}^S \geq 0, N_d \lesseqgtr 0} \quad & \gamma_d \left(\rho_d y_d^\sigma + (1-\rho_d) l_d^\sigma\right)^{\left(\frac{1}{\sigma}\right)} - ry_d - PN_d \\
\text{subject to:} \quad & E_d \leq \xi_d + N_d, \\
& y_d = \min\left\{\frac{k_{ds}}{\omega_{ds}}\right\}_{s=1}^S .
\end{aligned} \tag{1.4.12}$$

where N_d is the amount of permits that the firm buys (> 0) or sells (< 0) from the national

[22]Domestic offset supply includes domestic offsets supplied as well as all other domestic abatement from CCS, bio-electricity, and non-CO_2e sources as tracked by the EPA's analysis of ACESA. The EPA's analysis of ACESA used both the Intertemporal General Equilibrium Model (IGEM) and the Applied Dynamic Analysis of the Global Economy (ADAGE) model and was widely circulated two months prior to ACESA's passage.

[23]The model now reflects the fact that the purchase of international offsets comprises an income transfer from the domestic economy to the rest of the world. Note that $\sum_{d=1}^D x_d = PA^H + r\sum_{d=1}^D K_d + \sum_{d=1}^D \pi_d = PA^H + r\sum_{d=1}^D K_d + \sum_{d=1}^D f_d(y_d) - r\sum_{d=1}^D y_d - P\sum_{d=1}^D N_d = \sum_{d=1}^D f_d(y_d) - 0.8PA^I$, given $\sum_{d=1}^D y_d = \sum_{d=1}^D K_d$ and $\sum_{d=1}^D N_d = A$ given market clearing in the capital and permit markets.

permit market.[24] Given (1.4.12), the unconditional factor demands for the capital composite and intermediate capital goods are given, respectively, by: $y_d(r, P)$ and $k_{ds}(r, P)$. Likewise, permits are demanded or supplied according to $N_d(r, P, \xi_d)$, the supply of the final good is given by $X_d(r, P)$, and total firm profits equals the returns to the labor endowment, $\hat{\pi}_d$, plus the value of free permits provided to the firm under the federal climate bill, i.e. $\pi_d(r, P, \xi_d) = \hat{\pi}_d(r, P) + P\xi_d$.

Equilibrium

An *economic equilibrium* is a price pair, $r\left(\bar{E}_0, \boldsymbol{\theta}\right), P\left(\bar{E}_0, \boldsymbol{\theta}\right)$, and the resulting economic outputs given maximization of (1.4.11) subject to the private budget constraint, (1.4.1), (1.4.10), (1.4.12), and (1.4.5) such that markets clear:

$$
\begin{aligned}
&\sum_{d=1}^{D} K_d(r) = \sum_{d=1}^{D} y_d(r, P), \\
&\sum_{d=1}^{D} x_d(r, P, \pi_d(r, P, \xi_d)) = \sum_{d=1}^{D} X_d(r, P), \\
&\sum_{d=1}^{D} (\xi_d + N_d(r, P, \xi_d)) - A(P) = \bar{E}_0.
\end{aligned}
\tag{1.4.13}
$$

The *ex post federal decisionmaking equilibrium* for proposer p is the $\left(\bar{E}_0^p, \boldsymbol{\theta}^p\right)$ that solves (1.4.8) given the economic equilibrium that solves (1.4.13). Given that all legislators face an equal probability of being selected (reflecting an equal recognition rule), the *ex ante federal decisionmaking equilibrium* is the equal weighted sum of all the $p = 1, .., D$ *ex post* federal decisionmaking equilibria. In the analysis that follows, I report results for both the *ex post* equilibrium when Waxman is realized as the proposer which is the ACESA policy outcome

[24] Summing the constraint in (1.4.12) across all districts and imposing the national cap I have: $\sum_{d=1}^{D} E_d - A \leq \sum_{d=1}^{D}(\xi_d + N_d) \leq \bar{E}_0$. Note that for $P > 0$, permits have value to legislators and so they will maximize the allocation of free permits which occurs when $\sum_{d=1}^{D} \xi_d = \bar{E}_0$. Thus total emissions will be less than or equal to the national cap so long as the permit market clears according to: $\sum_{d=1}^{D} N_d \leq A$. We abstract from issues related to market power in permit markets as Montero (2009) finds no evidence that this has been a concern in other permit regimes.

used for calibration, as well as the *ex ante* equilibrium.

1.4.3 State Decisionmaking

State climate policy reflects horizontal competition in state-level emissions caps in the spirit of Zodrow and Mieszkowski (1986). I choose caps instead of taxes as my instrument of choice because this appears to be the preferred instrument used across many states and for consistency with my federal model.[25] The interest here is not just in explaining why some 'believer' states set unilateral climate policies, but also anticipating how 'skeptic' states may choose to undermine those emissions reductions strategically given that markets are linked and emissions leakage is pervasive. I consider two versions of the model: one in which permits/offsets can be purchased from outside one's state but only if they are additional, and one in which they cannot. Both models are similar to recent work by Ogawa and Wildasin (2009)[26] except that I consider emissions caps and not emissions taxes, I do not assume that capital in each district has the same emissions intensity (i.e. $\alpha_d \neq \alpha_k$ for any $d \neq k = 1, ..., D$), reflecting sectoral heterogeneity in the production of emissions between states, and I do not assume that decisionmakers ignore their impact on equilibrium prices when setting policies.[27]

[25] Twenty states have state-wide GHG emissions targets. Ten states have state-wide GHG caps on the electricity sector. There are also several regional GHG emission reduction initiatives that are based on cap and trade systems in various stages of development (the Regional Greenhouse Gas Initiative, the Midwest Greenhouse Gas Reduction Accord, and the Western Climate Initiative). In addition, 29 states have Renewable Portfolio Standards (RPS) and eight states have renewable portfolio goals, which mandate/target that certain quantities of renewables be used in electricity generation. Some of these policies permit trading to varying degrees.

[26] Oates and Schwab (1988) were the first to show that decentralized decision-making may achieve the first-best reduction in emissions under certain assumptions. They also show, however, that the ability for decentralization to achieve the first-best falls apart with emissions reductions being under-provided when a non-distortionary lump-sum tax instrument is not available, a result which extends the classic inefficiency of horizontal fiscal competition result of Zodrow and Mieszkowski (1986) to the environmental setting. More recent work by Ogawa and Wildasin (2009) extends this result for the case when districts are heterogeneous with respect to environmental preferences, endowments, and production technology. There, the equivalence between the decentralized equilibrium and the first-best hinges upon four important assumptions: that lump-sum and capital taxes are available, emissions spillovers are uniform, emissions are generated uniformly per unit of capital, and decisionmakers assume their choices have no impact on equilibrium prices.

[27] I abstract from interactions with state fiscal systems and the provision of local public goods. Thus, the cap/mandate I consider can be thought of as an emissions tax/subsidy coupled with a lump-sum transfer to the private budget constraint of the representative consumer located within the state. Since the provision of local public goods are not captured by the model, the precise fiscal distortion identified by Zodrow and

The first model captures how some states allow permits/offsets from outside one's state to count in meeting their targets, whereas the second model reflects those that do not. The first model allows equalization of marginal abatement costs between districts—as there is a single price of carbon across all states—and thus makes it cheaper to achieve emissions reductions. However, because GHG emissions are a global pollutant, this model implies that the state government with the greatest preferences for emissions reductions chooses the total emissions reduction, and all other states with lower preferences see no benefit from further emissions reductions and thus do not reduce emissions further. In the second model without trading, states choose local caps which must be met by reductions in emissions by local producers. As state decisonmakers account for the impact of their choices on equilibrium prices (i.e. they anticipate leakage), there is again a strategic capital effect that reflects the ability of the state to leverage capital markets through their cap/mandate choice, reflecting the relative size of the state (in terms of capital). This is an important feature of the model, as it explains why larger states may be more willing to set unilateral climate policy than small states (Kanbur and Keen, 1993).[28]

The representative consumer in each state elects a state government. State governments simultaneously select a cap, $\bar{E}_d$, conditional on the caps chosen by all other states, $\left\{\bar{E}_s\right\}_{s\neq d=1}^{D}$,

Mieszkowski (1986) and Oates and Schwab (1988) is not present here, although something similar emerges given that I relax the assumption that decisionmakers ignore their impact on equilibrium prices when setting policies. Finally, as I restrict my attention to a global pollutant, emissions spillovers here are absolute and hence completely uniform (i.e. $\beta = 1$).

[28]While state policy with trading and offsets is the more natural comparison to ACESA which assumes a large role in the ability of offsets to contribute to emissions reductions, some may find this characterization of state policy as unrealistic. In reality, state policy is somewhere in between the two models. Several states have passed Renewable Portfolio Standards (RPS) which establish consumption mandates which specify the share of renewable electricity to be blended into electricity generation. RPSs hope to achieve emissions reductions without specifying that polluting industries must emit less, but instead target a sector that under ACESA may supply offsets. While there is significant heterogeneity in RPS schemes between states, some states permit trading of renewable credits in order to comply with the RPS. In addition, some states have formed regional trading bodies with the end objective of establishing a regionally consistent climate policy, where trading would be permitted. Voluntary offsets markets exist that can be used to supply offsets to some of these regional climate initiatives without intervention by the federal government.

according to:[29]

$$\max_{\bar{E}_d \geq 0} \quad U_d\left(\bar{E}_d, \left\{\bar{E}_s\right\}_{s \neq d=1}^{D}\right)$$
$$\text{subject to:} \quad E_d\left(\bar{E}_d, \left\{\bar{E}_s\right\}_{s \neq d=1}^{D}\right) \leq \bar{E}_d. \tag{1.4.14}$$

The Economy Under State Climate Policies

When trading is permitted, I allow offsets to be supplied following (1.4.10). For consistency with the federal model, I again assume: $A(P) = 0.8A^I(P) + A^H(P)$. Consequently, aggregate surplus is defined as (1.4.11) when trading is allowed, and (1.4.2) otherwise, with the corresponding private budget constraints. Maximization of aggregate surplus subject to the private budget constraint provides the Walrasian demand for the private given by: $x_d(r, \pi_d)$, when trading is not allowed, and $x_d(r, P, \pi_d)$, when it is.

When trading is not permitted, the producer located in a given state maximizes profits according to:

$$\max_{y_d \geq 0, \{k_{ds}\}_{s=1}^{S} \geq 0} \quad \gamma_d\left(\rho_d y_d^{\sigma} + (1-\rho_d) l_d^{\sigma}\right)^{\left(\frac{1}{\sigma}\right)} - r y_d$$
$$\text{subject to:} \quad E_d \leq \bar{E}_d,$$
$$y_d = \min\left\{\frac{k_{ds}}{\omega_{ds}}\right\}_{s=1}^{S}. \tag{1.4.15}$$

Given (1.4.15), the unconditional factor demands for the capital composite and intermediate capital goods are given, respectively, by $y_d\left(r, \bar{E}_d\right)$ and $k_{ds}\left(r, \bar{E}_d\right)$. The supply of the final good is given by $X_d\left(r, \bar{E}_d\right)$, and total firm profits by $\pi_d\left(r, \bar{E}_d\right)$.

[29] This is not a model of conditional decisionmaking; either the federal government acts or states act, but not both. Conditional decisionmaking complicates things considerably and is beyond the scope of this paper. For a model that tackles this issue in a classical public finance setting, see Janeba and Wilson (2011).

When trading is allowed, the producer instead solves:

$$\begin{aligned}
&\max_{y_d \geq 0, \{k_{ds}\}_{s=1}^{S} \geq 0, N_d \lesseqgtr 0} && \gamma_d \left(\rho_d y_d^{\sigma} + (1-\rho_d)\, l_d^{\sigma}\right)^{\left(\frac{1}{\sigma}\right)} - r y_d - P N_d \\
&\text{subject to:} && \alpha_d y_d - N_d \leq \bar{E}_d, \\
& && y_d = \min \left\{ \frac{k_{ds}}{\omega_{ds}} \right\}_{s=1}^{S}, \\
& && \alpha_d y_d - N_d \leq E_d^{BAU},
\end{aligned} \tag{1.4.16}$$

where E_d^{BAU} is the state's emissions under the business as usual of no climate policy. Note that the last constraint in (1.4.16) can be thought of as the requirement that reducing states (e.g. those that select $\bar{E}_d < E_d^{BAU}$) are only willing to allow permits from non-reducing states (e.g. those that select $\bar{E}_d \geq E_d^{BAU}$) for which it can be proven that those permits actually reflect emissions reductions below their business as usual emissions levels. This reflects the fact that states that choose to reduce emissions can require that permits bought from non-reducing states must be additional relative to those states' historical emissions levels. Otherwise reducing states would not be willing to allow permits to be bought from those states, and would instead prefer the no-trading regime. Given (1.4.16), the unconditional factor demands for the capital composite and intermediate capital goods are given, respectively, by $y_d\left(r, P, \bar{E}_d\right)$ and $k_{ds}\left(r, P, \bar{E}_d\right)$. Demand/supply of permits is given by $N_d\left(r, P, \bar{E}_d\right)$, the supply of the final good by $X_d\left(r, P, \bar{E}_d\right)$, and total firm profits by $\pi_d\left(r, P, \bar{E}_d\right)$.

Equilibrium

When trading is not allowed, an *economic equilibrium* is the rate of return to capital, $r\left(\left\{\bar{E}_d\right\}_{d=1}^{D}\right)$, and the resulting economic outputs given maximization of (1.4.2) subject to the private budget constraint, (1.4.1), (1.4.15), and (1.4.5) such that markets clear:

$$\sum_{d=1}^{D} K_d(r) = \sum_{d=1}^{D} y_d\left(r, \bar{E}_d\right),$$
$$\sum_{d=1}^{D} x_d\left(r, \pi_d\left(r, \bar{E}_d\right)\right) = \sum_{d=1}^{D} X_d\left(r, \bar{E}_d\right). \tag{1.4.17}$$

The *state decisionmaking equilibrium without trading* is the vector of state caps, $\left\{\bar{E}_d\right\}_{d=1}^{D}$, that jointly solves (1.4.14) for all $d = 1, ..., D$ states given the economic equilibrium that solves (1.4.17). When trading is allowed, an *economic equilibrium* is a price pair, $r\left(\left\{\bar{E}_d\right\}_{d=1}^{D}\right), P\left(\left\{\bar{E}_d\right\}_{d=1}^{D}\right)$, and the resulting economic outputs given maximization of (1.4.11) subject to the private budget constraint, (1.4.1), (1.4.10), (1.4.16), and (1.4.5) such that markets clear:

$$\sum_{d=1}^{D} K_d(r) = \sum_{d=1}^{D} y_d\left(r, P, \bar{E}_d\right),$$
$$\sum_{d=1}^{D} x_d\left(r, P, \pi_d\left(r, P, \bar{E}_d\right)\right) = \sum_{d=1}^{D} X_d\left(r, P, \bar{E}_d\right),$$
$$\sum_{d=1}^{D} N_d\left(r, P, \bar{E}_d\right) - A(P) = \sum_{d=1}^{D} \bar{E}_d. \tag{1.4.18}$$

The *state decisionmaking equilibrium with trading* is the vector of state caps, $\left\{\bar{E}_d\right\}_{d=1}^{D}$, that jointly solves (1.4.14) for all $d = 1, ..., D$ states given the economic equilibrium that solves (1.4.18).

1.4.4 Alternative Regimes

I compare the solutions to the models of federal and state decisionmaking to three alternative policy regimes: 1.) the business as usual of no climate policy which is the solution to (1.4.7), 2.) the climate policy that maximizes *scientific welfare*, and 3.) the climate policy that maximizes *revealed surplus*.

The climate policy that maximizes scientific welfare is the national cap that solves:

$$\max_{\bar{E}_0} \quad \sum_{d=1}^{D} \left(x_d \left(r \left(\bar{E}_0\right), P \left(\bar{E}_0\right), \pi_d \left(r \left(\bar{E}_0\right), P \left(\bar{E}_0\right)\right)\right) - \kappa_d \left(r \left(\bar{E}_0\right)\right) - \kappa_d^H \left(P \left(\bar{E}_0\right)\right)\right) - \Phi \bar{E}_0, \tag{1.4.19}$$

where Φ is an estimate of the global external damages from GHG emissions taken from the scientific literature (\$25.00 per ton CO_2e).[30]

The climate policy that maximizes revealed surplus is the national cap that solves:

$$\max_{\bar{E}_0} \qquad \sum_{d=1}^{D} U_d \left(\bar{E}_0\right). \tag{1.4.20}$$

For both (1.4.19) and (1.4.20), this is given a solution to the producer's problem that closely follows (1.4.12), the supply of offsets given in (1.4.10), and the economic equilibrium defined in (1.4.13), except where $\xi_d = 0$ for all $d = 1, ..., D$.

1.5 Calibration

I evaluate the welfare implications of federal and state climate policies for the year 2021.[31] Data for the model comes from several sources which are summarized in Table 1.2. Table 1.3 provides a summary of the calibrated business as usual national economy and Table 1.4

[30] In 2010, the US Interagency Working Group on Social Cost of Carbon (IWGSCC) recommended a social cost of carbon for regulatory impact analysis by the federal government of \$7.00, \$27.09, and \$42.95 per ton CO_2e (adjusted to 2009\$), for discount rates of 5%, 3%, and 2.5%, respectively for the year 2020 (IWGSCC, 2010). These are global estimates of the external damages from climate change largely based upon the DICE, PAGE, and FUND integrated assessment models. In 2013, IWGSCC updated these estimates to \$12.36, \$44.29, and \$65.92 per ton CO_2e, for discount rates of 5%, 3%, and 2.5%, respectively (IWGSCC, 2013). IWGSCC also recommended that to calculate domestic effects to the US economy alone, that the global estimate should be multiplied by 7 to 23%, which reflects the direct benefit to the US (7-10% for a discount rate of 2.5 or 3), or the proportional benefit to the US given its share of global GDP (23%).

[31] While the ACESA climate bill provides a sequence of emissions caps and sectoral permit allocations for every year between 2012 and 2050, I select the year 2021 for my welfare analysis as the emissions reduction of 18.8% achieved by the cap in 2021 is closest to the average annual discounted emissions reduction achieved under ACESA across all 38 years (20.1%) when future emissions reductions are discounted at an annual rate of 2.9% (a simple mean of the Stern Review estimate and Nordhaus' preferred estimate). See Appendix Table 1.1 for a detailed summary of the caps and share vectors for other years.

summarizes business as usual emissions. Key elasticities are selected to match predictions from the EPA's IGEM Scenario 2 assessment of ACESA, the core analysis of ACESA that was widely circulated to legislators and their staffs prior to the law's passage on June 26th, 2009, in terms of: expected permit price, share of domestic and international offsets to industry abatement, and the gross efficiency costs to the US economy.[32]

Given the business as usual baseline and the key elasticities chosen to match the EPA's central cost estimates of ACESA, I am able to identify all the model parameters except legislators' revealed valuation for emissions, $\boldsymbol{\phi} = \{\phi_d\}_{d=1}^{D}$. I use the 2021 cap, $\bar{E}_0^{WM}$, and the vector of shares of the cap allocated to sectors, $\boldsymbol{\theta}^{WM}$, as well as the observed June 26th votes to recover what $\boldsymbol{\phi}$ would need to be such that the solution to the legislative bargaining model detailed in Section 1.4.2 replicates the observed ACESA cap, vector of cap shares, and votes, an effort that is in the tradition of McFadden (1975).[33] The $\boldsymbol{\phi}$ that is calibrated in this way concludes the calibration of the model and allows me to perform a welfare consistent evaluation of the ACESA climate bill to the state policy equilibrium and the three alternative policy regimes. As the recovery of this parameter is crucial to the analysis, additional details proceed below. Additional details on model calibration are provided in the Appendix, Section A.1.

1.5.1 Legislators' Revealed Valuation for Emissions

In order to have voted yes, a legislator's aggregate surplus under ACESA would need to exceed their aggregate surplus under business as usual, e.g. $U_d^{WM}(\phi_d) \geq U_d^{BAU}(\phi_d)$, following the vote constraint and optimization problem in (1.4.8).[34] It follows from this constraint

[32] Although, these estimates come from IGEM Scenario 2, both total emissions and GDP have been updated to reflect the most recent 2012 data. While ACESA allows for banking of permits and the Scenario 2 analysis assumes that significant amounts of offsets are added to the bank until 2029, I adjust the offset supply curves to reflect the average contribution of offsets to total abatement across all years of the policy, which is the amount of offsets that I assume are supplied in 2021.

[33] I treat six abstaining voters as no-voters.

[34] I note that for at least twelve districts, $\phi_d \geq \hat{\phi}_d$ must bind with equality in order for the observed $\boldsymbol{\theta}^{WM}$ to reflect the optimal policy. There are 14 sectors, of which I only allow permit shares to be allocated to 13 sectors (excluding 'other economic'). The proposer would prefer to assign a maximum share of permits to the sector in which s/he has the greatest exposure. Thus, the fact that I observe positive shares for the twelve remaining sectors is only possible if some voters require those permits in order to obtain their votes.

that yes voting legislators' true valuation for emissions, ϕ_d, would need to be greater than or equal to an estimate of their valuation for emissions, $\hat{\phi}_d$. That is $\phi_d \geq \hat{\phi}_d$, where the expression for $\hat{\phi}_d$ is given by imposing $U_d^{WM}(\phi_d) = U_d^{BAU}(\phi_d)$ and solving for ϕ_d, or:

$$\hat{\phi}_d = \left[\frac{\left(x_d^{BAU} - \kappa_d^{BAU}\right) - \left(x_d^{WM} - \kappa_d^{WM} - \kappa_d^{H,WM}\right)}{\left(E_0^{BAU} - \bar{E}_0^{WM}\right)} \right], \tag{1.5.1}$$

where $\left(x_d^{BAU}, E_0^{BAU}, \kappa_d^{BAU}\right)$ reflects the business as usual equilibrium and $\left(x_d^{WM}, \bar{E}_0^{WM}, \kappa_d^{WM}, \kappa_d^{H,WM}\right)$ reflects the 2021 ACESA equilibrium and policy.

Likewise, in order for no voting legislators to have opted out of joining the electoral coalition, it must be the case that they would be 'more expensive' for Waxman (the proposer) to add them to the coalition. Thus, while the vote constraint in (1.4.8) implies that $U_d^{WM}\left(\phi_d; \xi_d^{WM}\right) \leq U_d^{BAU}(\phi_d)$, in order for the 2021 ACESA policy to be a solution to (1.4.8) for no voting legislators, I also require that: $U_d^{WM}\left(\phi_d; \hat{\xi}_d^{WM}\right) \leq U_d^{BAU}(\phi_d)$, where $\hat{\xi}_d^{WM} = \max\left\{\xi_d^{WM}, \max\left\{\xi_d^{WM}\right\}_{d \neq p \in \mathbb{D}^{WM}}\right\}$.[35] Then $\hat{\phi}_d$ for no voters follows the expression in (1.5.1), except that $x_d^{WM}\left(\xi_d^{WM}\right)$ is replaced by $x_d^{WM}\left(\hat{\xi}_d^{WM}\right)$. Finally, given the reversal in the inequality in the voting constraint, for no voting legislators it must be the case that $\hat{\phi}_d \geq \phi_d$.

One way to finish calibrating the model is simply to assume that $\phi_d = \hat{\phi}_d$. This may be overly restrictive given the lumpiness of the underlying optimization problem, as it strictly imposes the lower bound for all yes voters and the upper bound for all no voters. To further improve this estimate, I incorporate data from the Pew Research Center. For several years, Pew has asked survey respondents the following question: "In your view, is global warming a very serious problem, somewhat serious, not too serious, or not a problem?," where a value

For these legislators, $\phi_d \geq \hat{\phi}_d$ must bind at equality. This coincides with the way in which the coalition was incrementally formed as discussed in Section 1.3, where here Henry Waxman is the proposing legislator.

[35]That is, the observed no voting legislators would have continued to vote no even if they were offered permits equal to the maximum of the permits they actually received, ξ_d^{WM}, or the maximum number of permits provided to all non-proposing yes voting legislators, $\max\left\{\xi_d^{WM}\right\}_{d \neq p \in \mathbb{D}^{WM}}$.

of 1 denotes "very serious" and 4 denotes "not a problem." I pool three years (2008-2010) of survey responses to this question to compute the median response of citizens to this question for each legislative district, ϕ_d^{PEW}.[36]

Since ϕ_d^{PEW} reflects survey responses, it is not possible to directly translate this into a measure which is consistent with the model. However, it does provide a measure of the intensity of climate beliefs which can be used to relax the assumption that $\phi_d = \hat{\phi}_d$, by exploiting the rankings and spread of ϕ_d^{PEW}. I construct a new valuation for emissions parameter, $\hat{\hat{\phi}}_d$, based upon the original $\hat{\phi}_d$, but which maps the spread of the Pew data to the $\hat{\phi}_d$ space. This allows me to calibrate $\phi_d = \hat{\hat{\phi}}_d$, where it will again be the case that $\phi_d \geq \hat{\phi}_d$ for yes voters, and $\phi_d \leq \hat{\phi}_d$ for no voters, with strict inequality holding for some. To do so, let μ^{PEW} and σ^{PEW} be the mean and standard deviation of the Pew estimate, respectively, and $\hat{\mu}$ be the mean of $\hat{\phi}_d$. Then define $\hat{\hat{\phi}}_d\left(\hat{\hat{\sigma}}; \hat{\phi}_d\right) = \left(\frac{\phi_d^{PEW} - \mu^{PEW}}{\sigma^{PEW}}\right)\hat{\hat{\sigma}} + \hat{\mu}$, if $\left(\frac{\phi_d^{PEW} - \mu^{PEW}}{\sigma^{PEW}}\right)\hat{\hat{\sigma}} + \hat{\mu} > \hat{\phi}_d$ for yes voters or if $\left(\frac{\phi_d^{PEW} - \mu^{PEW}}{\sigma^{PEW}}\right)\hat{\hat{\sigma}} + \hat{\mu} < \hat{\phi}_d$ for no voters, and $\hat{\hat{\phi}}_d = \hat{\phi}_d$, otherwise. Here $\hat{\hat{\phi}}_d$ is a function of $\hat{\hat{\sigma}}$, which is the standard deviation of $\hat{\hat{\phi}}_d$, which is unknown. I select the $\hat{\hat{\sigma}}$ that minimizes the overspread of the constrained $\hat{\hat{\phi}}_d$ (e.g. for whom $\hat{\hat{\phi}}_d = \hat{\phi}_d$) which is defined as: $L\left(\hat{\hat{\sigma}}; \hat{\phi}_d\right) = \left(\frac{\phi_d^{PEW} - \mu^{PEW}}{\sigma^{PEW}}\right)\hat{\hat{\sigma}} + \hat{\mu}$ if $\hat{\hat{\phi}}_d\left(\hat{\hat{\sigma}}; \hat{\phi}_d\right) \leq \hat{\phi}_d$ for yes voters or if $\hat{\hat{\phi}}_d\left(\hat{\hat{\sigma}}; \hat{\phi}_d\right) \geq \hat{\phi}_d$ for no voters, and zero, otherwise. Once $\hat{\hat{\phi}}_d$ has been calibrated for all non-proposing yes and no voters, I identify the environmental preferences for Waxman, $\hat{\hat{\phi}}_p$, numerically such that the *ex post* solution to (1.4.8) is precisely $\left(\bar{E}_0^{WM}, \boldsymbol{\theta}^{WM}\right)$.

[36] I use three surveys that surround the June 26$^{\text{th}}$, 2009 ACESA vote: the *Pew Research Center April 2008 Political Survey*, *October 2009 Political Survey*, and *October 2010 Political Survey*. The surveys report party identification by state, and so after first fitting a truncated extreme value distribution of pooled survey responses by party by state using Maximum Likelihood Estimation, I construct a mixture distribution for each congressional district using the party vote shares for each legislative district from the 2008 election and the 100 state by party estimated truncated extreme value distributions. The median of each mixture distribution for each congressional district is my Pew estimate. For districts that were uncontested in 2008, I use the split from the 2006 elections instead. A few districts were uncontested in both 2006 and 2008 (always for candidates of the same party). For those districts, I allow shares to equal 1 and 0. Since the Pew data covers the 48 contiguous states, ϕ_d^{PEW}, for the single district in Alaska and the two districts in Hawaii were set to reflect the mean value of yes or no voters given those districts' votes.

1.5.2 Welfare Measures Used for Policy Evaluation

$\hat{\phi}_d$—and by extension $\hat{\hat{\phi}}_d$—reflect the calibrated economic outcomes between the business as usual and ACESA equilibria and captures several important sources of heterogeneity between districts captured by the structural model. However, by recovering $\hat{\hat{\phi}}_d$ using the observed vote and 2021 ACESA climate policy, this parameter likely includes other unobservables which reflect observed vote behavior but which may not necessarily reflect legislators' true valuation for emissions.[37] Moreover, even if $\hat{\hat{\phi}}_d$ does reflect legislators' actual valuation for emissions, it is not the case that those valuations are necessarily based upon sound science. For these two reasons, $\hat{\hat{\phi}}_d$ may not be a valid welfare metric. However, as $\hat{\hat{\phi}}_d$ is recovered to match observed votes and the 2021 ACESA climate policy, $\hat{\hat{\phi}}_d$ acts as a residual that explains policy formation. Thus, $\hat{\hat{\phi}}_d$ reflects how legislators actually behave, and critically does not require that legislators value scientific estimates of external damages when setting policy.[38]

Consequently, in the analysis below I compare federal and state policies across two welfare metrics. The *scientific welfare* metric reflects the efficiency costs of a policy less the change in external damages from GHG emissions of \$25.00 per ton CO_2e. This takes the policies implied by $\hat{\hat{\phi}}_d$ as given, but evaluates the welfare of the resulting policies using Φ and not $\hat{\hat{\phi}}_d$.

The *revealed surplus* metric treats $\hat{\hat{\phi}}_d$ as a valid welfare valuation of emissions. The obvious virtue of providing this complementary, positive 'welfare' analysis is that it does

[37] I abstract from the ability of interest groups to divert the preferences of legislators, the role of political parties in affecting the political costs of voting, the ability of voters to strategically delegate representatives with views that diverge from their own, and the ability of legislators to horse trade across votes or engage in other strategic voting behavior. In addition, $\hat{\hat{\phi}}_d$ may reflect that legislators anticipate significant international carbon leakage from ACESA or that legislators may be skeptical regarding the EPA's cost estimates of ACESA.

[38] $\hat{\hat{\phi}}_d$ should be a valid predictor of state policy so long as the unobservables which are included in $\hat{\hat{\phi}}_d$ as a result of federal decisionmaking, equally impact state decisionmaking and that there are not additional unobservables which separately impact state decisionmaking. To the extent that the pertinent unobservables reflect things such as interest group behavior, then this is not likely a strong assumption as interest groups actively operate at both the federal and state levels. Other differences between states such as the organization of the state government and the rules administering the legislative process may also be relevant for state decisionmaking, but which may not be accounted for in the unobservables embedded within $\hat{\hat{\phi}}_d$.

not require one to impose their own priors as to what is, or is not, a valid valuation of the external damages of GHG emissions.

1.6 Numerical Results

1.6.1 Estimate of Revealed Valuation for Emissions

The first panel in Table 1.5 reports the average of legislators' revealed valuation for emissions ($\hat{\hat{\boldsymbol{\phi}}}$) broken down by vote on ACESA. The average revealed valuation across all legislators is negative \$0.09 per ton CO_2e, reflecting significant skepticism. This negative valuation is not a concern, since the revealed estimate reflects skepticism with respect to scientific estimates of the external damages of GHG emissions, the ability for policy to remedy the problem, moral choices as to whether anything should be done to address climate change, and may even reflect the fact that climate change may even result in external benefits for certain parts of the country. Relative to my preferred scientific estimate of the external damages of GHG emissions (Φ) of \$25.00 per ton CO_2e, the revealed valuation is noticeably smaller.[39] Yes voters are on average climate believers with average revealed valuation of emissions of \$0.12 per ton CO_2e. In sharp contrast, no voters have an average revealed valuation of emissions of -\$0.29 per ton CO_2e.

Figure 1.1 compares my calibrated estimates of $\hat{\boldsymbol{\phi}}$ and $\hat{\hat{\boldsymbol{\phi}}}$ to the Pew estimate, $\boldsymbol{\phi}^{PEW}$, after standardizing the estimates to have a mean of zero and standard deviation of one across all legislative districts.[40] With respect to the Pew estimate, I find a strong statistically significant difference (at the 1% level) between yes and no voters. For yes voters, the center of mass of $\hat{\boldsymbol{\phi}}$ is very close to the center of the Pew estimate, although my structural estimate has a tighter spread. For no voters, the center of mass of my structural estimate skews slightly to the left of center of the Pew estimate, although the spread is closer between the

[39] The scientific estimate reflects planet-wide damages from climate change whereas our revealed estimate should be thought as reflecting the revealed estimate of damages to that district from climate change which may reflect a surplus benefit, plus, perhaps, legislators' regard for damages to others outside of one's district.

[40] The standardization reconciles the fact that $\hat{\boldsymbol{\phi}}$ and $\boldsymbol{\phi}^{PEW}$ have different natural scales.

two estimates for no voters than for yes voters. That said, t-tests between the means of the two estimates for either yes or no voters find no statistically significant difference between the means of both mass pairs. As $\hat{\hat{\boldsymbol{\phi}}}$ uses information on the spread of $\boldsymbol{\phi}^{PEW}$ to improve upon $\hat{\boldsymbol{\phi}}$, $\hat{\hat{\boldsymbol{\phi}}}$ reflects a combination of both $\hat{\boldsymbol{\phi}}$ and $\boldsymbol{\phi}^{PEW}$. To summarize, self-reported climate beliefs from the Pew estimate are strongly correlated with votes for ACESA and my preferred calibrated estimate of those beliefs, $\hat{\hat{\boldsymbol{\phi}}}$, largely coincides with those that are self-reported.

The second panel in Table 1.5 reports the average revealed valuation of emissions for state decisionmakers given the $\hat{\hat{\boldsymbol{\phi}}}$ calibrated for federal legislators. For consistency with the model of federal decisionmaking, which reflects that decisionmaking is likely to consist of a coalition of climate believers, $\hat{\hat{\boldsymbol{\phi}}}$ for the state model is the population-weighted sum of the $\hat{\hat{\phi}}_d$ of the 51% of legislators with the largest $\hat{\hat{\phi}}_d$ located within that state.[41] The average revealed valuation across all states is \$0.31 per ton CO_2e. When trading and offsets are not permitted, states that decide to reduce their emissions (cap 'reducers') have a revealed valuation of emissions of \$4.33 per ton CO_2e, whereas states that increase their emissions (cap 'increasers') have a valuation of negative \$0.24 per ton CO_2e. When trading is allowed, these values are \$10.97 and \$0.09 per ton CO_2e for reducers and increasers, respectively. When trading is allowed, the state with the greatest revealed valuation (California) alone unilaterally reduces emissions, which implies the larger valuation for cap reducers relative to the no trading case in which six states reduce emissions.

1.6.2 The Emissions Implications of Federal and State Climate Policy

Table 1.6 compares the emissions implications of federal and state policies relative to the three alternative regimes. The first column reports the results for the *ex post* federal decisionmaking equilibrium when Waxman is realized as the proposer, which is simply the calibrated ACESA outcome. ACESA would have reduced emissions by 1,142.7 TgCO_2e, relative to business as usual. The bulk of these emissions reductions, 654.6 TgCO_2e, come

[41] This should be thought of as state decisionmaking as being driven itself by a legislative process that is dominated by climate believers.

from offsets which is consistent with the EPA's IGEM analysis of ACESA. No voters account for 377.1 $TgCO_2e$ of emissions reductions and yes voters for the remaining 111.0 $TgCO_2e$. As ACESA requires that all districts reduce their emissions by 15.2% relative to business as usual, the fact that no voters account for at least two-thirds of industry abatement reflects the fact that those districts were dis-proportionally larger emitters to begin with. This reflects the fact that, unsurprisingly, heterogeneity in the incidence of the cap across districts is strongly correlated with vote for ACESA and which is accounted for in my analysis. Relative to the policy that maximizes scientific welfare, ACESA undershoots by 113.3 $TgCO_2e$. In contrast, relative to the policy that maximizes revealed surplus, ACESA overshoots by 4,164.0 $TgCO_2e$, owing to fact that average negative revealed valuation for emissions reported in Table 1.5 implies that revealed surplus is maximized by choosing a cap that leads to more emissions than under business as usual.

The second column reports the results for the *ex ante* federal decisionmaking equilibrium. The results in this column follow those in the first except that the amount by which emissions are reduced is roughly half of those realized under ACESA. This is because, given the calibrated $\hat{\hat{\boldsymbol{\phi}}}$ which reflects the constraints which support ACESA as the solution to (1.4.8), yes voters offer policies that are almost exactly equal to what Waxman passed, whereas no voters offer no climate policy, and yes votes are slightly greater than half the votes for ACESA. Since the underlying dynamics are the same, I focus my attention on the *ex post* or ACESA equilibrium in the analysis that follows.

In sharp contrast to ACESA, state decisionmaking in which trading and offsets are permitted (column three) results in emissions reductions of just 177.4 $TgCO_2e$, relative to business as usual. One state, California, which has the greatest $\hat{\hat{\phi}}_d$ alone sets a stringent cap, equal to the total emissions reductions, of which 4.3 $TgCO_2e$ comes from California directly, 67.0 $TgCO_2e$ from all other states, and 106.2 $TgCO_2e$ from offsets. When trading is allowed the marginal cost of abatement is equalized between states and equal to the national permit price and the state with the greatest revealed valuation for emissions sets a cap that maximizes their aggregate surplus corresponding to that national permit price, which in this case is akin to California setting a national carbon tax. If California didn't act, other states would also set stringent caps but to a lesser extent given their revealed valuation for emissions are less than those of California. Thus, since national emissions reductions are determined by the California 'tax' and those emissions reductions exceed what those other states would like to adopt, they adopt non-stringent caps instead. Finally, some states do not wish to set stringent caps at all given their revealed valuation for emissions. Relative to the scientific welfare and revealed surplus maximizing policies, state policy with trading achieves too few emissions reductions of 1,078.6 $TgCO_2e$ and 3,198.7 $TgCO_2e$ too many emissions reductions, respectively.

When trading and offsets are not allowed (column four), state decisionmaking results in far fewer emissions reductions, just 12.8 $TgCO_2e$ relative to business as usual. When trading is not allowed, several states with sizable labor and capital bases and large valuations for emissions set stringent caps and thus reduce emissions. States with large capital bases are *ceteris paribus* more willing to reduce emissions than states with small capital bases because the producer surplus loss from supplying capital ($rK_d - \kappa_d$) for a marginal reduction in capital (a local cap) is smaller for states which supply a lot of capital. Likewise, states with large labor endowments witness a smaller relative decline in the returns to the labor endowment (π_d) from a marginal reduction in a local cap than states with smaller labor endowments. Emissions reducing states set caps to achieve emissions reductions of 89.9 $TgCO_2e$. As this causes the rate of return to capital, all other states increase their emissions by 77.0 $TgCO_2e$ in order to increase the returns to their fixed labor endowment. As was the case when trading and offsets were permitted, state policy without trading again achieves too few emissions reductions of 1,243.2 $TgCO_2e$ relative to the scientific welfare policy and 3,034.1 $TgCO_2e$ too many emissions reductions relative to the revealed surplus maximizing policy.

1.6.3 Welfare Implications of Federal and State Climate Policy

The top panel in Table 1.7 compares federal and state policies using the scientific welfare metric. Table 1.8 reports the welfare changes from Table 1.7 normalized by the corresponding changes in emissions from Table 1.6. Relative to business as usual, ACESA (column one) achieves a far greater scientific welfare gain of \$14.3 billion than either state policy, \$3.7 and -1.0 with (column three) and without trading and offsets (column four), respectively. This is a central result of this paper. From the perspective of scientific welfare, federal policy dominates state policy. While this coincides with the result found in Banzhaf and Chupp (2012) which examined federal and state policies to regulate local air pollution, this is for a fundamentally different reason here. The policies compared here emerge as a result of revealed valuations for emissions and do not assume that policymakers consider scientific estimates of the external damages of emissions when setting policy.

Following the undershooting of emissions reported in Table 1.6, ACESA leaves an additional scientific welfare gain of \$0.1 billion on the table. While federal policy is very close to being optimal from the basis of scientific welfare, this is purely coincidental and could not have not have been known *a priori*, as both federal and state decisionmaking are distortionary in my framework. Moreover, it should be noted that if one preferred an alternate value for the scientific estimate of the external damages, ACESA could undershoot emissions by more ($\Phi >$ \$25.00 per ton CO_2e), and thus leave even more welfare gains on the table, or overshoot emissions ($\Phi <$ \$25.00 per ton CO_2e), corresponding to excess efficiency costs from too much emissions reductions. In contrast, state policy with trading leaves \$10.6 billion of additional scientific welfare gains on the table, and state policy without trading and offsets \$15.4 billion.

The bottom panel of Table 1.7 evaluates federal and state policy using the revealed surplus metric. In sharp contrast to my earlier finding that federal policy scientific welfare dominates state policy, here both state policies lead to smaller revealed surplus losses than does federal policy. ACESA provides a revealed surplus loss of \$57.2 billion relative to business as usual.

State policy with trading and offsets results in a revealed surplus loss of \$7.4 billion, and state policy without trading and offsets a revealed surplus loss of \$1.8 billion. This reversal in dominance between the two metrics, is wholly a result of the calibrated $\hat{\hat{\phi}}$, which reflects significant skepticism among policymakers on average. Likewise, the dominance of state policy over federal policy when considering the revealed surplus metric also holds when comparing to the scientific welfare maximizing and revealed aggregate surplus maximizing policies.

The distributional outcomes across believers and skeptics between federal and state policy reveal a crucial insight into past support for climate legislation. Skeptics, which are more likely to prefer the revealed surplus metric, would prefer no policy and then state policy over federal policy as either state policy results in a smaller revealed surplus loss of \$4.3 and \$0.7 billion, for the respective trading and no trading cases, whereas federal policy results in a revealed surplus loss of \$80.4 billion to skeptics (e.g. the no voters under ACESA, or the cap increasers under state policy). In contrast, believers (e.g. yes voters and cap reducers), from the perspective of either scientific welfare or revealed surplus metric, achieve far greater welfare gains from federal policy of \$8.2 and \$23.2 billion, respectively, than the gains from the most favorable state policy in which trading and offsets are permitted of \$-1.0 and \$-3.1 billion.

1.6.4 Distributional Implications of ACESA Under Alternative Allocation Rules

Table 1.9 examines the emissions and welfare implications when the ACESA cap and the proposer are held fixed, but when permits are allocated to districts using alternative allocation rules. The top panel examines the implications if the proposer were able to perfectly target permits to districts (i.e. the proposer can directly allocate ξ_d to build the coalition), whereas the bottom panel examines the implications if permits were instead allocated to districts based upon their expected efficiency costs under the cap. As a cap imposes an equal incidence (in percentage terms) on all districts, I refer to this allocation rule as equal targeting.

Under perfect targeting, the proposer would shed one yes voter from the coalition, since passage of the bill would only require a majority of 218 votes. The legislator that is dropped received the largest amount of permits of all yes voters under ACESA equal to 22.7 $TgCO_2e$. This voter joins the coalition of no voters who receive an average of 12.4 $TgCO_2e$ under imperfect targeting and who now all receive zero permits. The average permits to yes voters under the original ACESA more than doubles owing solely to gains to the proposer.[42] The permits that went to no voters are all returned to the proposer, who now receives an enormous sum of 3,467.6 $TgCO_2e$ of permits compared to just 9.2 $TgCO_2e$ of permits under imperfect targeting. This reveals the critical difference in proposer power between the imperfect and perfect targeting models, and also reveals how far off my welfare estimates would be if I fit ACESA using a model of perfect targeting rather than my correct model of imperfect targeting.

Under equal targeting, all districts receive the exact same number of permits worth 11.3 $TgCO_2e$.[43] 174 yes voters under ACESA with imperfect targeting would continue to support the ACESA cap under equal targeting. In fact, those voters would receive an average increase in permits of 2.3 $TgCO_2e$ under equal targeting. In sharp contrast, 45 voters that voted for ACESA under imperfect targeting would not vote for ACESA under equal targeting.[44] Consequently, the ACESA cap would have failed the House by 44 votes (since only 218 votes are needed for passage). These voters would lose on average 4.1 $TgCO_2e$ worth of permits under equal targeting. In addition, no voters who voted against ACESA

[42]The proposer continues to offer roughly the same number of permits to yes voters remaining in the coalition, since the $\hat{\phi}_d$'s for the fixed cap were determined such that aggregate surplus under ACESA just equaled the aggregate surplus of these voters under business as usual.

[43]While the analysis that follows compares imperfect targeting under ACESA to an equal allocation of permits, it should be noted that similar distributional dynamics would likely emerge even if 100% of allowances were auctioned off, or if a carbon tax was used in lieu of a cap. As Pooley (2010) notes: "Any [carbon tax bill] would be shaped by the same regional forces that shaped ACESA. A carbon tax that failed to address them would never pass." This point is also acknowledged by Hahn and Stavins (2011).

[44]These "fence-sitters" are skewed geographically. 71.4% of these fence-sitters are from states that are not located in either the northeast or the west coast. Comparatively, yes voters from states not located in either the northeast of the west coast accounted for only 49.3% of all yes votes cast for ACESA.

with imperfect targeting would continue to vote but receive on average 1.0 $TgCO_2e$ fewer permits under equal targeting. Imperfect targeting, because it targets some industries that are vital to secure passage of the original cap, allows permits to be boosted to a critical segment of yes voters but in so doing also boosts the average permits of no voters. Critically, this occurs because the exposure of this segment of yes voters under the cap is correlated with the exposure of no voters. Since changes in welfare again follow changes in the permit allocation, imperfect targeting improves the welfare of all no voters relative to equal targeting while lowering the welfare of consistent yes voters.

1.6.5 Emissions and Welfare Implications of Federal Climate Policy Under Alternative Allocation Rules

The prior analysis has examined how alternative allocation rules impact the distribution of permits across districts as well the implications for votes for a fixed ACESA cap. However, the choice of allocation rule has important implications for the ability of federal policy to be hijacked; that is, for an especially stringent cap to be selected, not necessarily because external benefits from reducing emissions, but from the value of the free permits that are generated along with the cap.

Under an allocation rule in which permits are equally distributed, I find that there is actually no cap that would be able to pass the House. Thus, the resulting federal policy is no climate policy. From the perspective of the revealed surplus metric, this would actually be preferred to both ACESA and either state policy which result in greater revealed welfare losses relative to the aggregate surplus maximizing level.[45] From the perspective of scientific welfare, however, no policy would imply a greater welfare gain only relative to the state policy without trading and offsets case, and otherwise a scientific welfare loss.

Table 1.10 reports the results for the allocation rule in which the proposer can perfectly target just the amount of permits needed to secure the minimum winning coalition, holding

[45] This can be seen from comparing the business as usual baseline to the aggregate surplus maximizing baseline in the bottom panel of Table 1.7.

the proposer fixed. In this case, the proposer would select a considerably more stringent cap than the ACESA cap, resulting in an additional 73.2% reduction in emissions. This result is consistent with the intuition regarding hijacking in the model.[46] Moreover, while the cap under imperfect targeting undershot the scientific welfare maximizing emissions level by 113.3 $TgCO_2e$, the cap under perfect targeting overshoots the scientific welfare maximizing emissions level by 723.2 $TgCO_2e$.

Consequently, overshooting under perfect targeting results in a 88.96% smaller scientific welfare gain relative to business as usual. Relative to the scientific welfare maximizing policy, undershooting under imperfet targeting led to \$0.1 billion of additional welfare gains being left on the table, under perfect targeting this is an incredible \$12.7 billion loss. In effect, better targeting increases the returns from hijacking as the proposer is able to extract ever more permits for each additional reduction in emissions.

From the perspective of revealed surplus, the cap selected under perfect targeting results in a 113.6% greater welfare loss than that achieved by the ACESA cap relative to business as usual. Thus, perfect targeting result in too stringent a cap from the perspective of both scientific welfare and revealed surplus. This highlights the value of my empirical approach as it demonstrates how revealed policy choices can lead to different scientific welfare results depending upon how the allocation rule impacts decisionmaking. In addition, this result suggests that imperfect targeting may actually be preferred to a perfect targeting mechanism for allocating permits. Under perfect targeting, the improved ability to consume green pork results in overeating.

1.6.6 Would ACESA Have Passed the US Senate?

The state revealed valuation parameters provided in Table 1.5 reflect the preferences of Senators given that Senators are elected at large in each state. One implication of this is

[46]This also coincides with the theoretical result reported in Proposition 1 in Appendix Section A.2.1, which shows that the cap selected under perfect targeting will result in a significantly more stringent cap than under the imperfect targeting allocation rule of ACESA. The analytical result assumes that there is only heterogeneity in the revealed valuation for emissions, whereas the numerical model here permits heterogeneity across several important dimensions.

that the preferences of believers in a state partially wash out the preferences of skeptics. The result is that extreme preferences are tamped down by aggregating at the state level. Since the ACESA coalition in the House consisted predominantly of climate believers, this dilution will have important implications for the ability of ACESA to pass the Senate. I can evaluate this by passing the observed ACESA climate policy into my state model and counting the number of yes votes that result. I find that only 10 states or 20 senators would have voted for ACESA.

1.7 Conclusion

This paper developed a spatially and sectorally disaggregated model of the US economy in which emissions are generated. I then linked this economic model with models of federal and state decisionmaking that explicitly account for the role of disagreement over climate change on policy formation. Divergent revealed valuations for emissions impact decisionmaking across both levels of government in critically different ways. At the federal level, a legislative coalition is likely to choose a stringent cap (relative to the revealed surplus maximizing emissions level) and which will consist of climate believers who especially value emissions reductions as well as others who do not necessarily value emissions reductions, but instead the free permits or green pork that are jointly produced along with a national cap on emissions. At the state level, 'believer' states unilaterally reduce their emissions which are offset by 'skeptic' states who expand production in response to a lower rate of return to capital, and thus increase emissions.

Using the June 26$^{\text{th}}$, 2009 vote and the 2021 cap and permit allocation for ACESA, I recovered legislators' revealed valuations for emissions which allowed me to perform a welfare consistent comparison of federal and state policies (both with and without trading and offsets) relative to the business as usual policy, a policy that maximizes scientific welfare, and a policy that maximizes revealed surplus. I found that federal policy is likely to result in substantially greater emissions reductions than either of the two state policies, with federal policy causing emissions to fall by 1,142.7 $TgCO_2e$ relative to business as usual, whereas state policies resulted in emissions declines of just 177.4 and 12.8 $TgCO_2e$ for the trading and offsets and no trading and offsets cases, respectively. This has important welfare implications both in terms of the scientific welfare and revealed surplus metrics evaluated in the paper, providing the two central results of my analysis.

First, with respect to scientific welfare, I found that federal policy scientifically welfare dominates both state policies, with ACESA achieving a scientific welfare gain of \$14.3 billion and state policies achieving a gain of \$3.7 and a loss of \$1.0 billion for the trading and offsets and no trading and offsets cases, respectively. Neither federal nor state policies maximize scientific welfare, with federal policy leaving \$0.1 billion in additional gains on the table, and state policy with trading and offsets leaving \$10.6 billion.

Second, in sharp contrast to the first result, I found that no policy revealed surplus dominates both state policies which themselves dominate federal policy. State policy without trading and offsets results in a revealed surplus loss of \$1.8 billion, whereas state policy with trading and offsets achieves a loss of \$7.4 billion, and federal policy a loss of \$57.2 billion. This result emerges because I found significant skepticism with respect to climate change among policymakers in the US with legislators having an average revealed valuation for emissions of -\$0.09 per ton CO_2e, and because federal policy results in far greater emissions reductions than either state policy.

In addition, my analysis sheds light on the optimal strategies of both believers and skeptics and which appears to be confirmed by environmental and 'Tea Party' groups across the United States. Climate believers are more likely to support federal policy because it is more likely to achieve the emissions reductions that they value than will state approaches which are plagued by strategic leakage in the presence of climate disagreement. Consequently, believers are more likely to achieve both scientific welfare or revealed surplus gains from federal policy then from either state policy. Likewise, skeptics are more likely to support no policy first and foremost and then state policy over federal policy, since, from the perspective of revealed surplus which more better reflects their true valuations for emissions reductions, they are likely to achieve correspondingly smaller revealed surplus losses.

Finally, I demonstrated that the way in which permits were allocated under ACESA had very important implications both for the likelihood of federal policy passing as well as the welfare implications of the resulting cap. If permits were equally distributed to all legislators, I find that no federal climate policy would pass. The imperfect targeting of permits to certain sectors in which fence-sitting yes voters have high exposure demonstrates how green pork is essential to grease the wheels for the passage of climate policy. This mechanism also allows no voters to receive more permits on average than yes voters and helps offset the burden of climate policy on no voters who are likely to comprise the most polluting districts. If permits could be perfectly targeted to legislators at just the level necessary to secure their vote and no more (with no voters receiving no permits), then the resulting cap would be even more stringent. If permits were instead perfectly targeted to legislators directly, the scientific welfare gains from federal policy would fall by 88.9% or $12.7 billion, relative to the the federal policy that results given the imperfect targeting that occurred under ACESA. While imperfect targeting under ACESA undershot the scientific welfare maximizing emissions level by 113.3 $TgCO_2e$, if permits could be perfectly targeted, federal policy would overshoot instead by 723.2 $TgCO_2e$. More precise targeting of permits increases the returns from hijacking as the proposer is able to extract more green pork for each additional reduction in emissions, but in this case results in overeating. As a consequence, imperfect targeting may actually be preferred to a perfect targeting mechanism for allocating permits, although greater targeting also likely increases the probability of a policy passing.[47] This suggests that the choice of allocation rule has important scientific welfare implications for the revealed cap which are not obvious *a priori* and further demonstrates the value of my revealed approach.

The analysis performed in this paper is insightful, but it does have important limitations.

[47] This is not explicitly examined by my analysis, nor are the implications of targeting in the context of jointly passing a bicameral legislature.

The positive, revealed surplus metric used in the paper is valuable as it does not require one to impose their own prior regarding external costs. This is important, especially as policy debates over environmental policy, and other areas such as healthcare, continue to reveal a widening divide over the justification for government intervention to address market failures such as externalities. To the extent that these disagreements raise the costs of public policy by imposing significant constraints on policymaking, they should not be under-scrutinized or trivialized. That said, the revealed valuations for emissions that are calibrated through my empirical framework may reflect unobservables that I cannot fully disentangle, and which may not reflect true welfare. In particular, I abstract from the role of lobbying, strategic voting, etc. on policy choices, and so the revealed valuations will absorb these aspects. In addition, this measure may not reflect skepticism regarding climate change *per se*, but expectations that either federal or state policy may result in significant global leakage. Finally, perceived damages need not reflect the actual and significant damages that most scientists and economists acknowledge that climate change will bestow. To the extent that the unobservables reflect true welfare than the revealed surplus analysis that relies on these revealed valuations may not be too far off. Even if this is not the case, the revealed valuations for emissions act as a residual which explain observed policy choices and so should still be a valid predictor of endogenous policies to the extent that those unobservables explain federal and state decisionmaking equally. Thus the framework I have developed provides a compelling way for us to compare policies chosen as a result of perceived, although perhaps incorrectly so, impacts.

Secondly, my analysis has not considered simultaneous or sequential joint decisionmaking, nor interactions with global agreements. Third, in my evaluation of the welfare impacts of ACESA, I have abstracted from certain design elements such as renewable subsidies, border tariffs, and output-based rebating which may themselves have important distributional implications for economic and political agents. Future work should evaluate how these elements are likely to impact the distortionary implications of federal and state decisionmaking with respect to climate change. In addition, future work should exploit the stream of caps and permit allocations under ACESA to evaluate whether legislators discount the free permits under ACESA differently then the external benefits and efficiency costs of the cap and the implications this may have for the distortionary costs of federal decisionmaking.

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Table 1.1: ACESA Cap and Permit Allocation Schedules, 2012 to 2050

	2012	2015	2020	2025	2030	2035	2050	2021
Emissions Cap ($TgCO_2e$)	4,627.3	5,003.3	5,055.5	4,294.2	3,532.8	2,908.5	1,035.5	4,903.3
Share of Cap Going to Permits, Total	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Share to Economic Sectors	0.506	0.606	0.620	0.620	0.068	0.000	0.000	0.620
Electricity	0.438	0.389	0.350	0.350	0.000	0.000	0.000	0.350
Natural Gas	0.000	0.000	0.090	0.090	0.000	0.000	0.000	0.090
Heating Oil	0.019	0.017	0.015	0.015	0.000	0.000	0.000	0.015
Oil Refineries	0.000	0.020	0.020	0.020	0.000	0.000	0.000	0.020
Automobiles	0.030	0.030	0.010	0.010	0.000	0.000	0.000	0.010
Trade Vulnerable Industries	0.020	0.150	0.135	0.135	0.068	0.000	0.000	0.135
Share to Civic Sectors	0.494	0.394	0.380	0.380	0.933	1.000	1.000	0.380
Low Income Consumers	0.150	0.150	0.150	0.150	0.150	0.150	0.150	0.150
CCS Bonus Allowances	0.000	0.018	0.050	0.050	0.050	0.050	0.050	0.050
Renewable Energy	0.110	0.110	0.070	0.025	0.060	0.060	0.060	0.070
Domestic Adaptation	0.010	0.010	0.010	0.020	0.040	0.040	0.040	0.010
Investment in Workers	0.005	0.005	0.005	0.010	0.010	0.010	0.010	0.005
Building Codes	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
All Others	0.214	0.097	0.090	0.120	0.618	0.685	0.685	0.090

Table 1.2: Datasets Used to Calibrate the Model

Variable/Parameter	Description	Data Source
$\bar{E}_0^{WM}$, $\boldsymbol{\theta}^{WM}$	WM Climate Policy	*US EPA IGEM Analysis of WM*
$\bar{L}_d$	Labor Endowment by District	*US Census American Community Survey 2007*
π_0, K_0, r	National Returns to Labor, Capital Supplied, and Rate of Return to Capital	*US BEA GDP 2007*; *US BEA 2002 Input-Output Tables 2002*
π_d	Returns to Labor by District	*US Census American Community Survey 2007*
k_s	Capital Demand by Sector	*US BEA 2002 Input-Output Tables 2002*
E_0, E_s	Total Emissions and Emissions by Sector	*US EPA Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2010*; *US EPA IGEM Analysis of WM*
ω_{ds}, k_{ds}, y_d, K_d	Capital Demand and Shares by District and Sector, Capital Demand and Supplied by District by Sector,	*US Census County Business Patterns 2007*; *US EIA Annual Energy Review 2012*; *US EIA Fuel Oil and Kerosene Sales 2009*
δ_{ds} for $s = 8$	Poor Exposure	*US Census American Community Survey 2007*
δ_{ds} for $s = 9$	CCS Exposure	*US NREL NATCARB Saline 2012*; *Coal 2012*; and *Oil and Gas 2012 Datasets*
δ_{ds} for $s = 10$	Renewables Exposure	*US EIA Annual Energy Review 2012*; *US NREL Wind 25km 2011*; *Geothermal 2009*; *Urban Wood and Secondary Mill Residues 2012*; *Crop Residues 2008*; *Forest and Primary Mill Residues 2008*; *PV 10km Resolution 2012 Datasets*
δ_{ds} for $s = 11$	Adaptation Exposure	*USGS National Elevation Dataset 2012*; *US National Atlas Coastline One Million-Scale 2012*
δ_{ds} for $s = 12$	Workers Exposure	*US Census American Community Survey 2007*
δ_{ds} for $s = 13$	Building Exposure	*US EIA Residential Energy Consumption Survey 2009*
δ_{ds} for $s = 14$	Other Exposure	*US Census American Community Survey 2007*
P	Permit Price	*US EPA IGEM Analysis of WM*

Table 1.3: Characteristics of the Baseline Economy

	National	Congressional Districts
Economy		
Real GDP (billion 2009 dollars)	19,519.5	44.77
		(9.54)
Total Value of Labor	9,327.8	21.39
		(3.53)
Total Value of Capital	10,191.7	23.38
		(7.98)
Electricity	154.4	0.35
		(0.23)
Natural Gas	57.4	0.13
		(0.13)
Heating Oil	9.6	0.02
		(0.02)
Petroleum Refineries	118.2	0.27
		(0.74)
Automobiles	272.3	0.62
		(1.08)
Trade Vulnerable Industries	249.1	0.57
		(0.65)
All Other Economic Sectors	9,330.7	21.40
		(7.83)
Total Labor (million persons)	152.2	0.35
		(0.04)

Notes: Mean reported for congressional districts with standard deviation in parentheses. The seven sectors listed above are the economic sectors included in the model.

Table 1.4: Emissions in the Baseline Economy

	National	Congressional Districts
Total Emissions (Tg CO_2e)	7,448.8	17.21
		(16.00)
Electricity	2,118.4	4.86
		(3.18)
Natural Gas	1,171.7	2.69
		(2.75)
Heating Oil	95.3	0.22
		(0.25)
Petroleum Refineries	2,367.7	5.43
		(14.84)
Automobiles	0.0	0.00
		(0.00)
Trade Vulnerable Industries	337.9	0.77
		(0.89)
All Other Economic Sectors	1,413.2	3.24
		(0.00)
Covered By Cap	0.0	0.00
		(0.00)
Uncovered By Cap	1,413.2	3.24
		(0.00)

Notes: Mean reported for congressional districts with standard deviation in parentheses. The seven sectors listed above are the economic sectors included in the model.

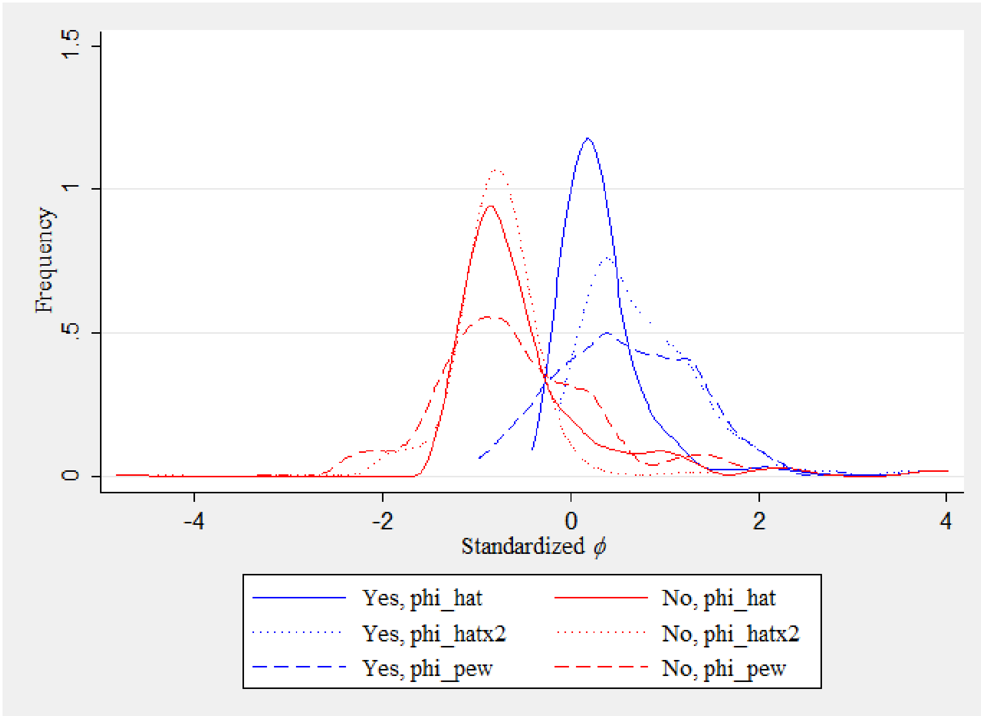

Figure 1.1: Comparison of Structural Revealed Valuation for Emissions to Pew Estimate

Table 1.5: Revealed Valuation for Emissions

	Number of States/ Districts	Average	Standard Deviation	Minimum	Maximum
Congressional Districts					
Revealed Valuation of Emissions (\$ per tonCO_2e)	436	-0.09	0.25	-1.20	0.86
For Yes Voters	219	0.12	0.17	-0.12	0.86
For No Voters	217	-0.29	0.13	-1.20	0.30
States					
Revealed Valuation of Emissions (\$ per tonCO_2e)	50	0.31	2.07	-3.16	10.97
For Cap Reducers, With Offsets	1	10.97	0.00	10.97	10.97
For Cap Increasers, With Offsets	49	0.09	1.38	-3.16	4.75
For Cap Reducers, No Offsets	6	4.33	3.30	0.92	10.97
For Cap Increasers, No Offsets	44	-0.24	0.87	-3.16	1.77

Notes: Revealed valuation of emissions is the calibrated $\hat{\hat{\phi}}$ times 1,000.

Table 1.6: Emissions Impacts of Federal and State Climate Policy

	Federal *Ex Post*	Federal *Ex Ante*	State With Offsets	State No Offsets
Emissions Under Business as Usual Policy (Tg CO_2e)	7,504.2	7,504.2	7,504.2	7,504.2
Emissions Under Climate Policy	6,361.5	6,930.2	7,326.8	7,491.4
Difference	-1,142.7	-574.0	-177.4	-12.8
Difference, From Offsets	-654.6	-328.8	-106.2	–
Difference, From Firm Reductions	-488.1	-245.2	-71.3	-12.8
Difference, Yes Voters/Cap Reducers	-111.0	-55.8	-4.3	-89.9
Difference, No Voters/Cap Increasers	-377.1	-189.4	-67.0	77.0
% Difference	-15.2%	-7.6%	-2.4%	-0.2%
Emissions Under Scient. Welf. Max. Policy (Tg CO_2e)	6,248.2	6,248.2	6,248.2	6,248.2
Emissions Under Climate Policy	6,361.5	6,930.2	7,326.8	7,491.4
Difference	113.3	682.1	1,078.6	1,243.2
% Difference	1.8%	10.9%	17.3%	19.9%
Emissions Under Rev. Surp. Max. Policy (Tg CO_2e)	10,525.5	10,525.5	10,525.5	10,525.5
Emissions Under Climate Policy	6,361.5	6,930.2	7,326.8	7,491.4
Difference	-4,164.0	-3,595.3	-3,198.7	-3,034.1
% Difference	-39.6%	-34.2%	-30.4%	-28.8%

Table 1.7: Welfare Impacts of Federal and State Climate Policy

	Federal *Ex Post*	Federal *Ex Ante*	State With Offsets	State No Offsets
Using Scientific Estimate of External Damages				
Agg. Surplus Under BAU (billion $)	13,241.8	13,241.8	13,241.8	13,241.8
Agg. Surplus Under Climate Policy	13,256.1	13,249.0	13,245.6	13,240.8
Difference	14.3	7.2	3.7	-1.0
Difference, Yes Voters/Cap Reducers	8.2	4.1	-1.0	-1.4
Difference, No Voters/Cap Increasers	6.0	3.0	4.7	0.4
% Difference	0.1%	0.1%	0.0%	0.0%
Agg. Surplus Under SWM (billion $)	13,256.2	13,256.2	13,256.2	13,256.2
Agg. Surplus Under Climate Policy	13,256.1	13,249.0	13,245.6	13,240.8
Difference	-0.1	-7.2	-10.6	-15.4
% Difference	0.0%	-0.1%	-0.1%	-0.1%
Agg. Surplus Under RSM (billion $)	13,091.0	13,091.0	13,091.0	13,091.0
Agg. Surplus Under Climate Policy	13,256.1	13,249.0	13,245.6	13,240.8
Difference	165.1	158.0	154.6	149.8
% Difference	1.3%	1.2%	1.2%	1.1%

Using Revealed Valuation Estimate				
Agg. Surplus Under BAU (billion $)	13,710.9	13,710.9	13,710.9	13,710.9
Agg. Surplus Under Climate Policy	13,653.8	13,682.2	13,703.6	13,709.1
Difference	-57.2	-28.7	-7.4	-1.8
Difference, Yes Voters/Cap Reducers	23.2	11.7	-3.1	-1.1
Difference, No Voters/Cap Increasers	-80.4	-40.4	-4.3	-0.7
% Difference	-0.4%	-0.2%	-0.1%	0.0%
Agg. Surplus Under SWM (billion $)	13,646.8	13,646.8	13,646.8	13,646.8
Agg. Surplus Under Climate Policy	13,653.8	13,682.2	13,703.6	13,709.1
Difference	7.0	35.4	56.8	62.3
% Difference	0.1%	0.3%	0.4%	0.5%
Agg. Surplus Under RSM (billion $)	13,749.0	13,749.0	13,749.0	13,749.0
Agg. Surplus Under Climate Policy	13,653.8	13,682.2	13,703.6	13,709.1
Difference	-95.2	-66.7	-45.4	-39.8
% Difference	-0.7%	-0.5%	-0.3%	-0.3%

Notes: BAU denotes the outcome under business as usual or no climate policy, SWM the policy that maximizes scientific welfare, and RSM the outcome that maximizes revealed aggregate surplus.

Table 1.8: Change in Aggregate Surplus Per Tg CO_2e of Emissions Reduced

	Federal *Ex Post*	Federal *Ex Ante*	State With Offsets	State No Offsets
Climate Policy Relative to BAU				
Change Using Scientific Estimate of Ext. Damages ($ per $TgCO_2e$)	-12.5	-12.5	-21.0	78.7
For Yes Voters/Cap Reducers	-7.2	-7.2	5.7	108.4
For No Voters/Cap Increasers	-5.3	-5.3	-26.7	-29.7
Change Using Revealed Valuation Estimate	50.0	50.0	41.6	141.2
For Yes Voters/Cap Reducers	-20.3	-20.3	17.4	85.4
For No Voters/Cap Increasers	70.4	70.4	24.2	55.7
Climate Policy Relative to SWM				
Change Using Scientific Estimate of Ext. Damages ($ per $TgCO_2e$)	-0.1	-0.1	-9.9	-12.4
Change Using Revealed Valuation Estimate	10.2	10.2	52.6	50.1
Climate Policy Relative to RSM				
Change Using Scientific Estimate of Ext. Damages ($ per $TgCO_2e$)	-45.9	-45.9	-48.3	-49.4
Change Using Revealed Valuation Estimate	26.5	26.5	14.2	13.1

Notes: BAU denotes the outcome under business as usual or no climate policy, SWM the policy that maximizes scientific welfare, and RSM the outcome that maximizes revealed aggregate surplus.

Table 1.9: Comparison of Alternate Allocation Rules Given ACESA Cap

Comparison of Imperfect Targeting to Perfect Targeting

	Imperfect Targeting	Perfect Targeting	Difference	% Difference	Votes
Average Permits Allocated, All Voters ($TgCO_2e$)	11.3	11.3	0.0	0.0%	436
Average Permits Allocated, Yes Voters	10.3	22.6	12.3	118.7%	219
That Voted For PT	10.3	22.7	12.4	120.9%	218
To Proposer	9.2	3,467.6	3,458.4	37,628.0%	1
To Other Yes Voters	10.3	6.8	-3.5	-33.6%	217
That Voted Against PT	22.7	0.0	-22.7	-100.0%	1
Average Permits Allocated, No Voters	12.4	0.0	-12.4	-100.0%	217

Comparison of Imperfect Targeting to Equal Efficiency Costs Targeting

	Imperfect Targeting	Equal Targeting	Difference	% Difference	Votes
Average Permits Allocated, All Voters ($TgCO_2e$)	11.3	11.3	0.0	0.0%	436
Average Permits Allocated, Yes Voters	10.3	11.3	1.0	9.8%	219
That Would Have Also Voted for ET	9.0	11.3	2.3	25.9%	174
That Would Not Have Voted for ET	15.4	11.3	-4.1	-26.5%	45
Average Permits Allocated, No Voters	12.4	11.3	-1.0	-8.3%	217

Notes: Imperfect Targeting (IT) reflects the allocation rule under ACESA in which permits are directly allocated to sectors, and then indirectly to legislators. Perfect Targeting (PT) assumes that the proposer can directly allocate permits to legislators. Equal Targeting (ET) assumes that all legislators receive an equal proportion of the total permit pool.

Table 1.10: Comparison of Optimal Policy Under Imperfect Targeting to Optimal Policy Under Perfect and Equal Targeting

	ACESA	Optimal With Perfect Targeting	Difference	% Difference
Change in Emissions and Permit Allocations				
Climate Policy to BAU ($TgCO_2e$)	-1,142.7	-1,979.2	-836.5	73.2%
Climate Policy to SWM ($TgCO_2e$)	113.3	-723.2	-836.5	-738.1%
Climate Policy to RSM ($TgCO_2e$)	-4,164.0	-5,000.5	-836.5	20.1%
Average Permits Allocated ($TgCO_2e$)	11.3	9.4	-1.9	-16.9%
To Yes Voters	10.3	18.9	8.5	82.5%
To Proposer	9.2	2,756.2	2,747.0	–
All Others	10.3	6.2	-4.1	-39.6%
To No Voters	12.4	0.0	-12.4	-100.0%

	ACESA	Optimal With Perfect Targeting	Difference	% Difference
Change in Agg. Surplus, Using Scientific Estimate of External Damages				
Climate Policy to BAU (billion $)	14.3	1.6	-12.7	-88.9%
To Yes Voters	8.2	63.0	54.7	–
To Proposer	-0.1	73.3	73.5	–
All Others	8.4	-10.4	-18.8	–
To No Voters	6.0	-61.4	-67.4	–
Climate Policy to SWM (billion $)	-0.1	-12.8	-12.7	12,585.7%
Climate Policy to RSM (billion $)	165.1	152.4	-12.7	-7.7%

	ACESA	Optimal With Perfect Targeting	Difference	% Difference
Change in Agg. Surplus, Using Revealed Valuation Estimate				
Climate Policy to BAU (billion $)	-57.2	-122.1	-65.0	113.6%
To Yes Voters	23.2	89.2	65.9	–
To Proposer	0.0	73.6	73.6	–
All Others	23.3	15.5	-7.8	–
To No Voters	-80.4	-211.3	-130.9	–
Climate Policy to SWM (billion $)	7.0	-58.0	-65.0	-930.2%
Climate Policy to RSM (billion $)	-95.2	-160.2	-65.0	68.2%

Notes: BAU denotes the outcome under business as usual or no climate policy, SWM the policy that maximizes scientific welfare, and RSM the outcome that maximizes revealed aggregate surplus. There is no solution when permits are distributed according to equal targeting. "Difference" column may not add up due to changes in the number of voters between policies.

Chapter 2

Are there Carbon Savings from US Biofuel Policies? The Critical Importance of Accounting for Leakage in Land and Fuel Markets

2.1 Introduction

Although the costs of comprehensive U.S. federal climate legislation, such as a cap-and-trade program, are shown to be rather small (CBO, 2009), a variety of political obstacles continue to block its passage. Policymakers have instead relied on sectoral and regional approaches to reduce greenhouse gas (GHG) emissions.[1] A major concern associated with sectoral and regional approaches to climate policy relates to their effectiveness in reducing GHG emissions (Bushnell et al. (2008), Goulder and Stavins (2011)). Such approaches are *incomplete*, in that only a subset of polluting sectors or regions are regulated. As a consequence they are likely to generate *carbon leakage*. Carbon leakage occurs as sectors or regions not covered by the regulation respond to the regulation (directly or indirectly) (Goulder et al. (2012)). When it comes to sectoral approaches to climate policy, policies that call for the expansion of liquid biofuels have been especially scrutinized by environmental groups and the popular press. Yet, to date very few studies have examined the carbon leakage that results from biofuel policies, and typically only consider a single source of leakage.[2]

The purpose of this paper is to provide comprehensive estimates of carbon leakage from the Renewable Fuel Standard (RFS) for conventional biofuels. The RFS mandates quantities of conventional and advanced biofuels, with each biofuel class defined according to its lifecycle emissions savings relative to gasoline.[3] The current RFS was established in 2007 when the Volumetric Ethanol Excise Tax Credit (VEETC)–the long-standing federal biofuel subsidy–was in place. However, the VEETC was allowed to expire at the end of 2011, leaving the

[1] Examples include the Renewable Fuel Standard (RFS) which mandates the use of liquid biofuels by the fuel sector, the Corporate Average Fuel Economy (CAFE) standards which mandate minimum fuel economy standards for passenger vehicles and light trucks, and Renewable Portfolio Standards (RPS), which establish state-level targets for renewable energy production by the electricity sector.

[2] Our use of the term ‘leakage’ is somewhat different than that of the literature that examines incomplete regulation. We refer to leakage as the additional GHG emissions that emerge in the economy as a result of market adjustments, relative to intended emissions savings that are calculated using lifecycle analysis (LCA).

[3] Lifecycle analyses (LCA) of GHG emissions attempt to measure all emissions attributable to a product, including the emissions resulting from the production, transportation and consumption of the product of interest, as well as the emissions resulting from the production and transportation of all inputs to the production process.

RFS as the primary biofuel support program in the U.S. Our analysis of the RFS explicitly accounts for these changes in policy regime, and reviews the impact of current proposals to eliminate the RFS for conventional biofuels altogether.

This paper addresses three related questions. First, what are the effects of the RFS on land and fuel markets? Second, what is the impact of the RFS on overall GHG emissions, and how does carbon leakage in land and fuel markets cause overall emissions to deviate from the intended emissions savings anticipated by legislators at the time the RFS was passed in 2007? Third, what is the impact of the change in policy regimes and current proposals to eliminate the RFS on overall GHG emissions and leakage due to the RFS?

Several prior studies have examined the emissions impacts of biofuels, although none have simultaneously examined these impacts in the context of past, current, and proposed policy regimes. One strand of the literature relies on lifecycle methods, without reference to a particular biofuel policy. For example, in their seminal work, Farrell et al. (2006) argue that the lifecycle emissions savings of ethanol relative to gasoline are 18%. Many studies recognize that biofuel policies can lead to various multi-market adjustments. However, most develop models to explicitly capture adjustments in *either* fuel (Khanna et al., 2008; de Gorter and Just, 2009; Rajagopal et al., 2011; Hochman et al., 2011; Drabik and de Gorter, 2011; Thompson et al., 2011; Rajagopal and Plevin, 2013) *or* land markets (Searchinger et al., 2008; EPA, 2010; Hertel et al., 2010), either abstracting from adjustments in the excluded markets altogether or assuming constant adjustments and/or emissions factors in the excluded market per unit of biofuel added. For example, Thompson and coauthors (2011) analyze the RFS in a framework that includes world fuel markets and U.S. agricultural markets, but do not link the emissions calculations directly to land market adjustments. Similarly, Rajagopal and Plevin (2013) perform a Monte Carlo analysis to quantify uncertainties in the GHG impacts of biofuel policies using a model of world fuel markets that includes emissions resulting from land market impacts as uncertain parameters that are constant per unit of fuel. The U.S. Environmental Protection Agency's (EPA) Regulatory Impact Analysis of the RFS (EPA, 2010), which is the most comprehensive analysis of the RFS to date, considers the GHG implications of biofuels expansion using several sophisticated domestic agricultural and global land use models, but does not quantify the GHG implications that result from adjustments in fuel markets. There are a few studies that consider both land and fuel markets. A set of studies uses the Biofuel and Environmental Policy Analysis Model (BEPAM), which integrates U.S. land and world fuel markets, to analyze first and second generation biofuel policies along a number of dimensions. Chen et al. (2012) examines the changes in domestic land use and emissions resulting from the RFS in 2022. Chen et al. (2011) compares the welfare implications of the RFS, LCFS and a carbon tax in 2030. Huang et al. (2013) examines the welfare and GHG impacts of combining the RFS with a LCFS and carbon price policy. A common feature of the BEPAM analyses is that biofuel policies will cause large expansions in cellulosic ethanol and feedstocks, and relies on assumptions by the EIA regarding future penetration of E-85 automobiles.

Our study differs from earlier work in several ways. First, we develop an analytic and numerical multi-market model that consistently integrates fuel, food and land markets. We link this multi-market model with a sectorally disaggregated emissions model. While some studies (e.g. Chen et al. (2011) and Huang et al. (2013)) also examine the impact of the RFS on total emissions using models that integrate land and fuel markets, our goal is to understand how the emissions consequences of the RFS differ from those intended. We derive an analytical formula that decomposes the overall change in GHG emissions that result from an increase in the RFS into *intended emissions savings* and *carbon leakage*. *Intended emissions savings* are calculated with standard lifecycle methods that reflect the GHG emissions savings resulting from replacing a unit of gasoline with a unit of ethanol, scaled up by the amount of ethanol added to the economy as a result of the RFS. *Carbon leakage* emerges from adjustments in land and fuel markets, both domestic and international, as the RFS impacts key prices. This decomposition is of critical importance to public policy as it directly illustrates the dangers of including LCA metrics in federal legislation as a criteria to select biofuel feedstocks.[4] The analytical formula guides the presentation of our simulation results, and provides a consistent frame of reference for comparing the magnitudes of leakage under various policy regimes and parameter assumptions. Our numerical results uncover a co-dependency between land and fuel market leakage that reflects the underlying economic relationships. For example, policy regimes with less land market leakage emerge because the policy causes smaller increase in the price of corn per liter of ethanol added. As a result, the price of blend fuel is more likely to decline, resulting in larger fuel market leakage. This suggests that the integration of land and fuel markets is critical for estimating leakage from either market, and for quantifying the total change in GHG emissions due to biofuel policies.

Second, we examine the RFS through the lens of past, current, and proposed policy regimes and therefore are able to shed light on how policy interactions and changes in policy play an important role in the direction and magnitude of leakage due to the RFS. Relative to a baseline that includes the VEETC we consider two policy regimes, one in which the RFS is added to the pre-existing VEETC and a second regime in which the RFS replaces the pre-existing VEETC. We include the VEETC in the baseline in our central analysis because this allows us to understand the emissions implications of the RFS from the perspective of policymakers at the time the RFS was enacted. The first policy regime allows us to isolate the impact of just adding the RFS to the economy and reflects the policies in place prior to 2011. The second regime allows us to isolate the impact of replacing the VEETC with the RFS–jointly removing the VEETC while imposing the RFS–and reflects the policies in place from the end of 2011. To understand the implications of current legislative proposals to eliminate the conventional RFS entirely, we consider a third policy regime that examines the impact of adding the RFS to a baseline without the VEETC in place.

Third, by focusing on the RFS for conventional biofuels through 2015 our estimates of

[4] Bento and Klotz (2013) show that lifecycle metrics are likely to be misleading measures of the emissions impacts of policy options supporting alternative technologies. They argue that the effectiveness of LCA as a policy tool could be improved if policies were the focus of the analysis and if the economic framework underlying the LCA includes the primary markets impacted by the policy.

the emissions resulting from RFS will be unencumbered by assumptions regarding second generation biofuels. We are able to safely ignore second generation biofuels because mandated and realized volumes of second generation biofuels are likely to be negligible over the time horizon of our study.[5] An analysis of the RFS through 2022 would require strong assumptions to dictate the emergence of second-generation biofuels, such as farmers willingness to plant second-generation feedstocks, the yields of second generation feedstocks, the marginal costs of producing second generation biofuels, and the emergence of E-85 vehicles. These assumptions will also affect price adjustments in land and fuel markets, and therefore leakage, due to the RFS.

Our central finding is that the expansion of biofuels mandated by the RFS can increase or decrease GHG emissions depending on the policy regime being evaluated. Relative to a baseline that includes the VEETC, the RFS increases emissions by 4.5 $TgCO_2e$ in 2015 with our central parameters.[6] Emissions increase because the intended emissions savings due to the RFS are offset by considerable leakage in land and fuel markets, 80% and 60% of intended emissions savings respectively. In contrast, swapping the pre-existing VEETC with the RFS expands domestic ethanol production while reducing GHG emissions, which indicates that allowing the VEETC to expire in 2011 provided emissions benefits. Emissions fall because swapping the VEETC for the RFS reverses the direction of fuel market leakage, which is sufficient to induce a reduction in total emissions of 2.0 $TgCO_2e$ in 2015 and a cumulative reduction in emissions of 25.5 $TgCO_2e$ between 2012 and 2015. Relative to a baseline in which the VEETC is not in place, the RFS increases emissions because leakage in land and fuel markets again offsets intended emissions savings. This suggests that current proposals for eliminating the RFS for conventional biofuels would reduce emissions by 6.7

[5]There is considerable uncertainty with respect to whether second generation biofuels will actually be required at the statutory levels specified in EISA because the EPA can scale down the blend requirements for cellulosic biofuels if there is a lack of cellulosic ethanol production capacity.

[6]That the RFS increases emissions relative to a VEETC baseline is robust to parameter assumptions. Across 81 combinations of parameter assumptions we find that the RFS increases emissions in 2015 in 78% of cases, with the change in emissions ranging from a small decrease of 2.2 $TgCO_2e$ to an increase of 27.8 $TgCO_2e$.

$TgCO_2e$ in 2015.

The rest of this paper is organized as follows. Section 2.2 provides details regarding the policy context of this paper. Section 2.3 develops an analytical model that decomposes the intended emissions savings and carbon leakage from a marginal change in the RFS. Section 2.4 presents simulation results, and Section 2.5 concludes.

2.2 Policy Details

Although biofuels in the U.S. are supported by a variety of policies at both the state and federal levels, here we focus on two of the most consequential federal policies: the Renewable Fuel Standard (RFS) for conventional biofuels and the Volumetric Ethanol Excise Tax Credit (VEETC). Details regarding other policies that impact ethanol production in the U.S. are provided in the Appendix.[7]

2.2.1 Renewable Fuel Standard (RFS)

The RFS was established by the Energy Independence and Security Act of 2007 (EISA) with rule-making authority provided to the EPA (US Congress, 2007). The RFS is a set of nested mandates specifying the minimum amount of various classes of biofuels that must be blended into the nation's fuel supply, where biofuels are classified according to the lifecycle GHG emissions savings they achieve relative to a fossil fuel derived alternative (gasoline or diesel). The national RFS targets all biofuels that achieve a reduction of at least 20%.[8] Below the national RFS, the RFS for advanced biofuels targets all biofuels that achieve a savings of at least 50%. Since conventional biofuels such as corn ethanol do not meet this threshold, we define the *RFS for conventional biofuels* as the national RFS less the RFS for advanced biofuels. Within the RFS for advanced biofuels, there are separate standards for "cellulosic biofuel", which targets biofuels that must achieve emissions savings of 60% or

[7]An appendix that contains supporting text, the mathematical structure of our numerical model, details on data and parameters for calibration, and additional results is available at www.joelrlandry.com.

[8]Specifically, only biofuels from new facilities that commenced construction after December 19, 2007 must meet this standard. Production from facilities built prior are grandfathered in under EISA 2007.

more, and “biomass-based diesel” which targets biodiesel that must achieve savings of 50% more.

The RFS for conventional biofuels expands from 15.1 billion liters in 2006 to 56.7 billion liters in 2015, after which it remains constant through 2022. The RFS for conventional biofuels applies only to those biofuels that achieve a 20% or greater lifecycle emissions savings. The (EPA, 2010) has determined that domestically produced corn ethanol just meets this requirement, achieving lifecycle savings of 21%. It is widely expected that this mandate will be predominantly filled by corn ethanol, given that it is the most cost competitive biofuel in widespread production in the U.S.

There are legitimate reasons to question whether the volumes originally set for advanced biofuels will be achieved in the short run, including the EPA's statutory authority and past willingness to scale down the cellulosic ethanol mandate, current technical limits on the amount of ethanol that can be blended into fuel (the so-called “blend wall”), and constraints on the expansion of ethanol imports.[9] Given this, as well as the lack of credible data on feedstock production and technological conversion efficiency for advanced biofuels, we do not consider the RFS for advanced biofuels in our analysis. A complete discussion regarding our decision to abstract from the RFS for advanced biofuels is provided in the Appendix.

Recently, a bipartisan effort in the House has proposed the RFS Elimination Act (HR 1461), which would eliminate the corn ethanol requirements of the RFS, lower the Advanced RFS, and prohibit ethanol blends greater than 10%. Similar proposals have been offered in the Senate as amendments to the Farm Bill that is currently under debate.

2.2.2 Volumetric Ethanol Excise Tax Credit

The VEETC was an excise tax credit (deducted from the federal fuel tax) of $0.12 per liter provided to fuel blenders for each unit of ethanol they added into the fuel supply. The

[9]EISA 2007 includes a “cellulosic loophole” which effectively allows the EPA to scale down the RFS for cellulosic biofuels if production capacity to meet the mandated quantities does not exist. Using this authority, the EPA has lowered the required volumes of cellulosic biofuels to less than 7% of the level set by EISA 2007 in 2010, 2011 and 2012.

VEETC expired at the end of 2011, nearly half a decade after the RFS was first established. Prior to its expiration, ethanol production had been subsidized since the 1978 Energy Tax Act. The VEETC was by far the most significant federal support program for biofuels until the RFS was established. Under a non-binding RFS, the VEETC acted as an implicit agricultural support program; however under a binding RFS, the VEETC provides no additional support beyond that provided by the binding RFS.[10] Consequently, the expiration of the VEETC in 2011 provides a useful frame of reference for understanding whether policymakers intended to replace the VEETC with the RFS, a case we explicitly examine below.

2.3 Analytical Model

In this section we develop an analytical model that integrates fuel, land and food markets to decompose the overall emissions resulting from the RFS into intended emissions savings and carbon leakage in land and fuel markets.

2.3.1 Economic Model

General Environment

We develop a static model of two countries, D and W, both open economies. D denotes the United States. W represents the rest of the world, a collection of open economies that trade with the U.S. The countries freely trade agricultural crops and crude oil.[11] All other goods are assumed to be immobile. Therefore, the prices of crops and crude oil are determined on

[10] Although the expiration of the VEETC was initially opposed by feedstock and ethanol producer groups, many of these groups eventually acquiesced, largely, it appears, due to the presence of the RFS. According to Matthew A. Hartwig of the Renewable Fuels Association: "We may be the only industry in U.S. history that voluntarily let a subsidy expire... The tax incentive is less necessary now than it was just two years ago We don't expect the price of corn to fall or rise just because the tax incentive goes away. We will produce the same amount of ethanol in 2012 as in 2011, or more." (Pear, 2012). This statement reflects the logic of a tax credit in the presence of a binding mandate. Since the binding mandate determines the amount of ethanol produced in the economy and therefore also the equilibrium price of corn in the economy, the VEETC no longer serves as a support program for corn and ethanol production. We believe that the VEETC would have been renewed had the RFS not been in place given the adeptness of these same groups to retain subsidies for ethanol in some form or other for over thirty years, as well as the continual renewal of the renewable Production Tax Credit (PTC) or "wind tax credit" even in the current legislative climate.

[11] We abstract from the trade of gasoline. Between 2005 and 2009, the U.S. imported less than 3% of total finished gasoline consumed, and exported less than 5% of total gasoline produced (U.S. Energy Information Administration).

the world market, while all other prices are determined domestically. The U.S. implements the RFS for conventional biofuels. We model explicitly the behavior of the agents in the U.S. economy, and treat adjustments in the rest of the world more simply.[12]

Consumer Demand

The representative household receives utility from blended fuel (F), food (X) and a composite consumption good (C). The representative household is endowed with land ($\bar{A}$) and labor ($\bar{L}$). The household's utility function is represented by:

$$U(F, X, C) \tag{2.3.1}$$

where $U(\cdot)$ is continuous and quasi-concave, and whose budget constraint is given by:

$$P_F F + P_X X + C = \bar{L} + \pi_{\bar{A}} \tag{2.3.2}$$

where P_F is the price of blended fuel and P_X is the price of food and the wage rate is normalized to unity. $\pi_{\bar{A}}$ is the net returns to the land endowment. The household chooses F, X, and C to maximize utility (2.3.1) subject to (2.3.2). From the resulting first-order conditions we obtain the uncompensated demand functions for blended fuel, food and the composite good are given by:

$$F(P_F, P_X, \pi_{\bar{A}}) \qquad X(P_F, P_X, \pi_{\bar{A}}) \qquad C(P_F, P_X, \pi_{\bar{A}}). \tag{2.3.3}$$

[12]When describing the U.S. portion of the model, we omit the subscript D as appropriate for ease of notation.

Fuel Production

Blended fuel is produced from gasoline (G) and ethanol (E) with a constant returns to scale production function given by:[13]

$$F = F(G, E). \tag{2.3.4}$$

The RFS is modeled as a share mandate for ethanol in the production of blended fuel:[14]

$$E \geq \theta F \tag{2.3.5}$$

where θ is the mandated share of ethanol per unit of blended fuel, such that the RFS mandated quantities are achieved.[15]

[13]Here we present a general formulation for the production of blended fuel. In the simulation model below, we assume that gasoline and ethanol are energy equivalent perfect substitutes. This appears to be the most common specification used (see de Gorter and Just (2009)). We believe this is an appropriate representation because consumers, when they purchase blended fuel at the pump, are largely unaware of the share of ethanol in the fuel they are purchasing. Consumers are, however, sensitive to the fuel economy of the blended fuel they purchase with respect to various retailers, which sell different (unlabeled) ethanol blends. Others authors, however, have somewhat different representations, including Vedenov and Wetzstein (2008) who assume perfect complements, and Ando et al. (2010), who consider a flexible constant elasticity of substitution (CES) specification. With respect to the latter, input-substitution is very sensitive to the share parameter in the CES function, which is calibrated to base year data. Since the share of ethanol in blended fuel has expanded exponentially over the last decade, this is very restrictive when compared to the perfect substitutes production function, in which the share of ethanol in blended fuel in the absence of the RFS is solved for endogenously without regard to the calibration year share of ethanol in blended fuel.

[14]We note that EISA established a trading program to ease compliance with the RFS, whereby each unit of biofuel produced is assigned a unique Renewable Identification Number (RIN). These RINs can be separated from the biofuel sold, and can thus be traded independently of the biofuel itself. Individual blenders are required to have enough RINs and/or RIN enumerated ethanol blended into their annual production, so that they meet their individual portion of the RFS (their Renewable Volume Obligation). Since we model a nationally representative fuel blender in order to evaluate a federal policy, spatial smoothing using RINs is not an issue. In effect, this assumes that the market for RINs is efficient and that the RIN market closes in each year.

[15]While the RFS itself states the total amount of biofuel that must be used, in practice the EPA annually determines the minimum share of ethanol that must be mixed into each liter of blended fuel. The blend requirement is set such that, given projected demand for blended fuel, the resulting total consumption of ethanol in a given year approximately equals the RFS (US EPA, 2010). A related concern affects the extent to which ethanol as an input in blended fuel is restricted due to technical limitations that are largely under the regulatory purview of the EPA. This so-called ‘blend-wall’ currently restricts the amount of ethanol that can be mixed into blended fuel to be 10% or less. Since our analysis is of the RFS for conventional biofuels through 2015, our model predicts that we just remain under this blend wall, and consequently this is not a concern for our analysis.

The fuel blender chooses E and G to minimize production costs:

$$P_G G + (P_E - \tau)E \tag{2.3.6}$$

subject to equation (2.3.4) and (2.3.5), where P_E and P_G, are the prices of corn ethanol and gasoline respectively and τ is the VEETC. The resulting price of blended fuel, is given by:

$$P_F(P_G, P_E - \tau, \theta) \tag{2.3.7}$$

and the final input demand functions for gasoline and ethanol are:

$$G = g_F(P_G, P_E - \tau)F(\cdot) \qquad E = e_F(P_G, P_E - \tau)F(\cdot) \tag{2.3.8}$$

where $g_F(\cdot)$ and $e_F(\cdot)$ are respectively the per unit conditional factor demands for gasoline and ethanol, and $F(\cdot)$ is the uncompensated demand for blended fuel from (2.3.3).

Gasoline and ethanol are produced by perfectly competitive firms with constant returns to scale production technology; gasoline is produced from crude oil, R_G, and labor, L_G, and ethanol is produced from corn, Y_E, and labor, L_E.[16] The production functions for gasoline and ethanol are given by:[17]

$$\begin{aligned} G &= G(R_G, L_G) \\ E &= E(Y_E, L_E). \end{aligned} \tag{2.3.9}$$

The price of gasoline can be written as a function of the price of crude oil, $P_G(P_R)$, and

[16] Here Y_E is net of co-products, which can be used in livestock rations. In the simulation model, co-products are produced jointly with ethanol and substitute for corn and soybeans in the production of food. See the Appendix for additional details.

[17] While we assume a flexible constant elasticity of substitution functional form to characterize gasoline production, consistent with literature estimates we use an elasticity of substitution that effectively implies a perfectly complementary relationship between labor and crude oil.

the price of ethanol can be written as a function of the price of corn, $P_E(P_Y)$. Finally the conditional factor demand functions are given by:

$$Y_E(P_Y, E(\cdot)) \qquad L_E(P_Y, E(\cdot)) \qquad R_G(P_R, G(\cdot)) \qquad L_G(P_R, G(\cdot)) \tag{2.3.10}$$

where $E(\cdot)$ and $G(\cdot)$ are from (2.3.8).

Agricultural Production

The representative household maximizes the net returns to its land endowment by allocating land to the production of crops, or setting land aside in the Conservation Reserve Program (CRP), for which it receives an annual rental payment.[18] Cropland can be allocated to corn production, Y, which can be used to produce food or ethanol, and other crops, Z which are used exclusively for food production.[19] Land enrolled in the CRP is indexed by N.[20]

Letting i index the three uses, $\{Y, Z, N\}$, the allocation of the land endowment is deter-

[18]The CRP is a government funded program, administered by the USDA, which allows farmers to voluntarily take historical cropland out of agricultural production in exchange for an annual rental payment. There are four major CRP programs, with varying contract lengths, payment rates and enrollment qualifications. Two of these programs, the Conservation Reserve Enhancement Program (CREP) and the Farmable Wetland Program (FWP) target specific environmental objectives and offer higher rental rates making this land unlikely to be converted to cropland. We therefore assume that only land in the remaining two major programs, general sign-up and continuous non-CREP, will be available for conversion to cropland. Thus, when we refer to 'CRP' land we are referring only the sum of these two sub-categories. Of these two categories, general sign-up provides the bulk of our measure of CRP, constituting on average 92% of our CRP measure between 2003 and 2010.

[19]In our simulation model, we disaggregate Z further and consider soybeans, hay, wheat and cotton.

[20]We abstract from other domestic land uses, such as pastureland, forest land and rangeland. According to the 2007 Natural Resources Inventory, between 2002 and 2007, the transition of land between cropland, forestry and range was small relative to the transition of land between pasture and cropland U.S Department of Agriculture (2009). 2002 rangeland and forestland constituted 0.2% of 2007 cropland, which is well within the margin of error reported for 2007 cropland (+/-0.75%). In contrast, 2002 pastureland accounts for 0.8% of 2007 cropland. On net, these small values reflect the fact that much of what constitutes rangeland, forest land, and pastureland is of considerably lower quality than cropland and/or has a high cost of conversion. To account for pasture, we include in our estimate of cropland, land used to produce continuous hay as reported by the USDA. We think that this is the component of pastureland most likely to be brought into agricultural production since it reflects cultivable pastureland.

mined by:

$$\pi_{\bar{A}}(P_Y, P_Z, \bar{A}) = \max_{A_i} \sum_i \left(P_i y_i(A_i) - l_i\right) A_i$$

subject to:

$$\sum_i A_i \leq \bar{A} \tag{2.3.11}$$

where P_Y and P_Z are world crop prices, A_i is the quantity of land allocated to land use i and l_i is the amount of labor required per unit land to produce crop i. The functions $y_Y(A_Y)$ and $y_Z(A_Z)$ represent the yields of corn and other crops respectively. The function $y_N(A_N)$ is treated as the per unit land CRP rental payment in dollars, so P_N is set to one. $y_i(A_i)$ are assumed to be monotonically decreasing and concave to reflect decreasing returns to expanded agricultural production and decreasing rental payments for land held in CRP.

In practice, a portion of total CRP acreage comes up for annual renewal as contracts expire, and land that is not up for renewal may also be converted but at the cost of a sizeable penalty which must be paid by the landowner.[21] The changes in CRP predicted by our model are meant to reflect expiring contracts, and for a given year are below the average amount of CRP land that is up for annual renewal.[22] We assume that CRP contracts are never broken, and therefore abstract from this mechanism of CRP conversion.

[21]CRP contracts have an initial length of 10 to 15 years, but can be extended later for shorter periods. We do not model these contracts explicitly. In addition, we do not explicitly model the environmental benefits of land held in CRP as a requisite for entry into the program. Consequently, cropland exiting the program is likely to be of a lower-quality than cropland remaining in the program, suggesting that any expansion in cropland resulting in reductions in land held in CRP will have marginally lower yields. To implicitly capture this issue, in our specification of the land-allocation problem (see Appendix), we allow yields for each crop considered and rental payments for land held in CRP to be declining in new acreage added. Finally, since we do not track land parcels, we choose emissions coefficients for the conversion of CRP that reflect that land in set aside from cropland may be of lower quality or have a limited soil carbon stock (see the discussion regarding emissions factors in Appendix).

[22]Given the frequency of past general sign-ups and renewals, on average approximately 1.3 million general sign-up hectares will come up for renewal for each year between 2010 and 2015 (U.S Department of Agriculture, 2008). We calibrate the supply of CRP land to reflect the annual flow of CRP land that comes up for renewal in a given year. We never find more than a third of these 1.3 million hectares being converted in a given year. In Appendix Section B.7 we validate these changes in CRP to changes observed in recent years. In general, the changes predicted by our model are consistent with those observed in recent years.

The first-order conditions of (2.3.11) provide the crop supply functions, as well as the optimal allocation of land to the CRP:

$$\begin{aligned} Y(P_Y,&P_Z,\bar{A}) = y_Y\left(A_Y(P_Y,P_Z,\bar{A})\right)A_Y(P_Y,P_Z,\bar{A}),\\ Z(P_Y,&P_Z,\bar{A}) = y_Z\left(A_Z(P_Y,P_Z,\bar{A})\right)A_Z(P_Y,P_Z,\bar{A}),\\ A_N(P_Y,&P_Z,\bar{A}). \end{aligned} \tag{2.3.12}$$

Food Production

Food is produced from corn and other crops by competitive firms with constant returns to scale technology:[23]

$$X = X(Y_X, Z_X, L_X) \tag{2.3.13}$$

where Y_X, Z_X and L_X are the quantities of corn, other crops and labor used in food production respectively. Incorporating food production in the model allows us to explicitly capture the trade-off between demand for crops for food production, and demand for crops for ethanol production. The food producer chooses Y_X, Z_X, and L_X to minimize production costs $P_Y Y_X + P_Z Z_X + L_X$ given the food production technology and taking prices as given. Given the demand for food from (2.3.3), the conditional factor demands for corn and other crops are:

$$Y_X(P_Y, P_Z, X(\cdot)) \qquad Z_X(P_Y, P_Z, X(\cdot)) \tag{2.3.14}$$

and $P_X(P_Y, P_Z)$ is the price of food.

Crop Export Demand

The rest of the world responds to the RFS only through price channels. We consider a simplified model of crop exports and specify the rest of world excess demand for U.S. crop

[23] We treat food as a composite of all final food products. As such our food sector encompasses intermediate sectors such as livestock production. We note that while livestock production is emissions intensive, we do not explicitly model the livestock sector because the RFS is expected to have a limited impact on emissions from livestock production (EPA, 2010).

exports:

$$Y_{X,W} = Y_{X,W}(P_Y, P_Z) \qquad Z_{X,W} = Z_{X,W}(P_Y, P_Z). \tag{2.3.15}$$

To account for land use change in the rest of the world, we assume that for each unit of crop exports displaced results in a constant quantity of rest of world non-agricultural land (which we treat as a composite of land uses including forest, grassland, shrubland and savanna among others) being converted to cropland.[24]

Crude Oil Supply

The rest of world excess supply curve for crude oil is given by:[25]

$$R = R(P_R). \tag{2.3.16}$$

We let $R_W(P_R)$ denote the rest of world demand for crude oil that underlies the excess supply of crude oil.

[24]We take a reduced form approach here in order to provide a transparent accounting of emissions arising from rest of world land use change. Given the uncertainty regarding the mechanisms of land use adjustment EPA (2010); Searchinger et al. (2008); Hertel et al. (2010) and the elasticity of the aggregate supply of cropland Barr et al. (2011), we vary the rate at which reduced crop exports are translated to rest of world land use change in sensitivity analysis. Further, we vary the emissions generated by land use change in the rest of the world, which implicitly reflects the makeup of land converted to cropland in the rest of the world. This allows us to account for the possibility that land converted to cropland is predominantly converted from uses with small or large carbon stocks, such as pasture or forest respectively.

[25]Studies suggest that OPEC operates as an imperfect cartel Griffin and Xiong (1997). Although we do not explicitly model market power in this market, in the sensitivity analysis below, we do examine the implications of price responsiveness on total emissions and leakage, by varying the elasticity of excess supply.

Equilibrium

An equilibrium consists of a price vector, P_Y, P_Z, P_R, such that the world markets for agricultural crops (Y and Z) and crude oil:

$$
\begin{aligned}
Y_D &= Y_{X,D} + Y_{E,D} + Y_{X,W} \\
Z_D &= Z_{X,D} + Z_{X,W} \\
R &= R_{G,D}
\end{aligned}
\tag{2.3.17}
$$

and the labor market in the U.S. clears and the government budget is balanced.[26]

2.3.2 Greenhouse Gas Emissions

We link the economic model above with a disaggregated model of greenhouse gas emissions (GHG) given by:

$$
GHG = \phi_G G + \phi_E E + \phi_Y A_Y + \phi_Z A_Z + \phi_{N,D} A_{N,D} + \phi_{N,W} A_{N,W} + \phi_R R_W \tag{2.3.18}
$$

where ϕ_i are GHG emissions released per unit of good or activity i (where i spans the economic sectors previously enumerated), and all quantities and emissions factors are specific to country D unless otherwise indexed.[27]

Intended Emissions Savings of the RFS

Given that the RFS has adopted lifecycle emissions savings as the primary metric for assessing the emissions impacts of biofuels, we use this metric to calculate the *intended emissions*

[26] Although not discussed above, the government finances the VEETC, CRP payments, and a lump sum transfer to the representative agent from a non-distortionary labor tax. The lump-sum transfer is also searched for under the identifying equation that the government's budget is balanced.

[27] While marginal emissions coefficient for gasoline is inclusive of the emissions from both gasoline consumption and production, we consider only the emissions from ethanol production because the carbon stored in ethanol and released during ethanol combustion, is absorbed from the atmosphere during the growth of corn (IPCC, 2007).

savings of the RFS.[28] Emissions in excess of those intended correspond to emissions leakage. Standard lifecycle metrics of corn ethanol rely on two critical simplifying assumptions. First, it is assumed that for every additional unit of ethanol produced, a constant quantity of land, $\tilde{A}_Y$, is brought into cultivation to grow the corn needed to produce that unit of ethanol.[29] Second, each unit of ethanol is assumed to displace an energy equivalent unit of gasoline. We demonstrate in the simulation results that these two assumptions will not hold if the RFS has an impact on equilibrium prices. As documented in Bento and Klotz (2013) lifecycle metrics can fail to account for the full emissions implications of the RFS and are likely to be a poor criteria on which to evaluate the emissions impacts of alternative biofuel policy options. With intended emissions savings defined in this manner, leakage measures the impact of the RFS on emissions net of increased emissions from the expanded production of ethanol and corn calculated using lifecycle methods and emissions reductions from a one-to-one displacement of gasoline with ethanol.

[28] While EISA established mandates for fuels based upon their meeting a GHG intensity threshold, analyses at the time of passage regularly inferred emissions savings given the expected amount of ethanol added by the policy and the expected GHG intensity of the fuels. Our characterization of intended emissions savings thus reflects the understanding of the EPA at the time EISA was passed. For example, the EPA's Regulatory Impact Analysis of RFS1, which was conducted just prior to EISA's passage in 2007 EPA (2007) assumes a GHG intensity for corn ethanol that ignored fuel market and world land market leakage and assumed that emissions from domestic land market adjustments were very small. We note that our characterization of intended emissions savings has no bearing on the net emissions results of our analysis.

[29] Letting $\lambda_{E,Y}$ represent the per-unit factor demand for corn for ethanol production, then $\tilde{A}_Y = \frac{\lambda_{E,Y}}{y_Y}$, where y_Y is the yield for corn, which is assumed to be independent of land already devoted to corn.

2.3.3 The Effects of the RFS on Greenhouse Gas Emissions

Consider a marginal increase in the RFS. The resulting impact on GHG emissions can be decomposed as (See Appendix for full derivation):

$$
\begin{aligned}
\frac{dGHG}{d\theta} = & \underbrace{\left(\phi_E + \phi_Y \tilde{A}_Y - \phi_G\right) \frac{dE}{d\theta}}_{I} \\
& + \underbrace{\underbrace{\phi_Y \left(\frac{dA_Y}{d\theta} - \tilde{A}_Y \frac{dE}{d\theta}\right)}_{L^Y} + \underbrace{\phi_Z \frac{dA_Z}{d\theta}}_{L^Z} + \underbrace{\phi_{N,D} \frac{dA_{N,D}}{d\theta}}_{L^N}}_{L^{DA}} \\
& + \underbrace{\phi_{N,W} \frac{dA_{N,W}}{d\theta}}_{L^{WA}} + \underbrace{\phi_G \frac{dF}{d\theta}}_{L^{DF}} + \underbrace{\phi_R \frac{dR_W}{d\theta}}_{L^{WF}} .
\end{aligned}
\tag{2.3.19}
$$

I, the first term on the right-hand side of equation (2.3.19), represents the *intended emissions savings* of the RFS. The intended emissions savings equals the (per-unit) lifecycle emissions savings of ethanol relative to gasoline, which is the term $(\phi_E + \phi_Y \tilde{A}_Y - \phi_G)$, multiplied by the change in ethanol due to the RFS. The lifecycle emissions savings of ethanol is the sum of the per unit emissions of ethanol production and the emissions from the corn required to produce a unit of ethanol, net of the lifecycle emissions of an energy equivalent unit of gasoline. I is linear in the amount of ethanol added by the RFS, $\frac{dE}{d\theta}$, and therefore fails to completely capture the impact of the RFS on emissions that stem from price adjustments. We call these price adjustment driven effects leakage.

The remaining terms on the right-hand side of equation (2.3.19) decompose the sources of carbon leakage in land and fuel markets. The first term, L^{DA} denotes *leakage from the domestic land market* and arises from three sources. The first two sources, $L^Y + L^Z$, comprise leakage from the intensive margin of land use. L^Y, isolates leakage from changes in food and export demand for corn. L^Z isolates leakage from changes in food and export demand for other crops. L^Y is equal to the total change in emissions from corn production, less the change in emissions from corn production that are attributed to expanded ethanol production in the calculation of I.

Both L^Y and L^Z are negative. The RFS will drive up all crop prices, but more so the price of corn, leading to two effects: a reallocation of cropland, and a reduction in the amount of crops demanded by the domestic food producer and rest of world crop exporters. As a result, the *actual* expansion of land allocated to corn production at the expense of other crops—adjustments along the intensive margin—are less than what are predicted by lifecycle methods, since price adjustments are ignored. Therefore, leakage from the intensive margin of land use is negative, implying emissions reductions that are beyond those accounted for in I. Negative leakage from the intensive margin of land use does not mean that emissions from domestic agriculture decline. Rather, L^Y and L^Z are negative because emissions from corn production are over accounted by the lifecycle methods that determine intended emissions savings.[30]

The third source of leakage from the domestic land market, L^N, represents leakage from the extensive margin of land use. L^N is equal to the lifecycle emissions benefits of CRP land multiplied by the change in land allocated to the CRP. Unlike leakage from the intensive margin, L^N is positive. As the RFS increases the prices of corn and other crops, the net returns to cropland also increase. In response, some land held in CRP is converted to cropland. Given that land held in CRP provides emissions benefits, this adjustment causes emissions to increase, a source of positive leakage. *A priori*, it is not possible to infer whether leakage from the domestic land market will be positive or negative. The direction depends on the magnitude of the negative leakage from the intensive margin relative to the positive leakage from the extensive margin.

L^{WA} denotes *leakage from the world land market* and equals the emissions benefits from non-agricultural land in the rest of the world, multiplied by the change in world land allocated to non-agricultural uses.[31] In response to the RFS, U.S. crop exports will fall. In order to

[30] As discussed in the results section, we find that the RFS will cause total emissions from domestic agriculture to increase.

[31] We note that the lifecycle assessment conducted by the U.S. EPA to categorize biofuels for the RFS incorporates both domestic and international land use adjustments (EPA, 2010). For comparison to EPA's

replace these lost exports, the rest of the world will expand cropland at the expense of non-agricultural land, leading to positive leakage as the climate benefits of non-agricultural land are lost.

Together, L^{DA} and L^{WA} make up total *land market leakage.* Whether land market leakage is positive or negative cannot be directly inferred from the analytical model.

L^{DF} denotes *leakage from the domestic fuel market* and equals the lifecycle emissions of gasoline multiplied by the change in blended fuel due to the RFS. Depending on the degree to which prices of ethanol and gasoline change in response to the RFS, as well as the share of ethanol in blended fuel, the RFS could impact the price and consumption of blended fuel (de Gorter and Just, 2009). However, the direction of the change in blended fuel, which determines whether L^{DF} will be positive or negative, is ambiguous.[32] A binding RFS will increase demand for ethanol, and therefore corn, causing the price of ethanol to increase relative to a counterfactual equilibrium without the RFS. In turn, the RFS will reduce the demand for gasoline which will lead to a decrease in the price of gasoline.

L^{WF} denotes *leakage from the world crude oil market* and equals the emissions from crude oil consumption multiplied by the change in rest of world crude oil demand due to the RFS. This term unambiguously is positive because the RFS reduces U.S. demand for gasoline and therefore crude oil. This depresses the world price of crude oil and leads to increased world consumption of crude oil, corresponding to positive leakage.

The sum of L^{DF} and L^{WF} make up total *fuel market leakage.* Fuel market leakage can be positive even if global fuel use declines.[33] Intended emissions savings include a measure of the emissions reduction from displaced gasoline, based on the assumption that each unit

assessment, L^{DA} and L^{WA} would be included in their estimate of intended emissions savings. We maintain our simple definition of I because it allows us to cleanly illustrate the mechanisms of each source of land use leakage. Moreover, it is not clear *a priori* whether the joint determination of a fuel and land market equilibria will affect L^{DA} and L^{WA}.

[32]The blended fuel sector is a key feature of our framework because, unlike previous studies of greenhouse gas emissions from biofuels such as EPA (2010), we do not restrict the rate at which ethanol displaces gasoline to be one-to-one.

[33]In our model, total world consumption of petroleum based fuels includes domestic gasoline and ROW crude oil. In our simulations we find that total world consumption of petroleum based fuels declines, but that leakage from fuel markets can be positive or negative.

of ethanol added by the RFS displaces an energy equivalent unit of gasoline, and ignores any change in rest of world crude oil use. Positive fuel market leakage signifies that the reduction in gasoline assumed to occur when calculating intended emissions savings over predicted the total reduction in global fuel use. Thus, fuel market leakage will be positive unless domestic fuel market leakage is sufficiently negative to offset positive leakage in the world crude oil market.

2.4 Numerical Results

We supplement the analytical model developed above with a numerical model that we use to quantify each of the terms in equation (2.3.19) for the years 2009-2015. Our central analysis compares the RFS to a baseline in which the VEETC is in place through 2015. This implicitly assumes that, in the absence of the RFS, policymakers would have otherwise continued to support biofuels through the VEETC which is fully consistent with the U.S.'s long history of biofuel support through subsidization. This baseline is also consistent with our characterization of intended emissions savings, as the reduction in emissions anticipated by a representative policymaker at the time that the RFS was enacted, since the VEETC was in place at this time.

Relative to a baseline that includes the VEETC, our central analysis considers two policy regimes. Our first policy regime imposes the RFS, while retaining the VEETC already in place through 2015. This simulation isolates just the contribution of the RFS relative to a pre-existing policy regime that includes the VEETC. With the RFS in place, however, it is less clear whether policymakers intended to keep both the RFS and VEETC in perpetuity, and as noted earlier the VEETC was allowed to expire at the end of 2011. Therefore, relative to the same baseline that includes the VEETC, we consider a second policy regime in which the RFS is imposed but the VEETC is removed for all years through 2015. This simulation isolates the effects of swapping the VEETC with the RFS. We keep the VEETC in the baseline because in the absence of the RFS it is likely that policymakers would have continued to support ethanol production through the VEETC. While these two analyses aim to capture recent changes in biofuel regimes, our simulations compare each regime for all years through 2015. Thus, the latter policy regime compares a baseline with the VEETC to a counterfactual of just the RFS for all years, not just from 2012 onward following the expiration of the VEETC at the end of 2011.

In addition to our central analysis, we evaluate the RFS relative to a baseline in which the VEETC is absent. This isolates the contribution of the RFS under the assumption that the VEETC had never been in place. It also allows us to evaluate the emissions implications of recent proposals to eliminate the RFS for conventional biofuels, given that the VEETC has expired and would not be reintroduced. We note that the fundamental economic intuition that explains this case is very similar to our central assessment of the RFS when the VEETC is renewed. For succinctness, we report the change in ethanol added by the RFS for this case in Table 2.2 and the total change in emissions in Table 2.8, but omit the intermediate tables that decompose the sources of leakage.[34] We also use this case to discuss the implications of our analysis to other studies that have assumed constant land market leakage.

A full discussion of the functional forms used in our numerical model, the data sources used to calibrate the model parameters and emissions factors, how the model parameters dynamically evolve over time, and the justification of central, upper and lower (used in sensitivity analysis) parameter values is left for the Appendix. In Table 2.1 we present several of the key elasticities and emissions factors used in the numerical model. These are consistent with literature values.

Model Validation

While we calibrate the model using 2003 data, we allow the model to run for each year between 2004 and 2009. This provides five years of model predictions that we can be compared against observed data in order to validate the baseline predicted by our model. Over this

[34] Appendix Tables B.14 and B.15 provide intermediate results for the analysis of the RFS relative to a baseline without the VEETC.

period either the RFS was not in place (pre-2006) or resulted in ethanol volumes significantly above mandated levels (post-2006), and thus was not binding. The full results of this analysis are presented in Appendix Table B.8. In general, our model performs quite well especially in light of the highly variable crop and crude oil prices over this period. On average between 2004 and 2009, we slightly underpredict observed harvested acreage for corn, soybeans, and CRP acreage by 1.78%, 0.56%, and 1.50%, respectively, while overpredicting wheat by 1.08%. Our predicted ethanol baseline over-predicts by 8.62% on average.

2.4.1 Impact of RFS on Ethanol and Intended Emissions Savings

The first row of Table 2.2 displays the baseline estimates of ethanol quantities with the VEETC in place. Rising crude oil prices and improvements in crop yields drive up the amount of ethanol in the economy from 40.1 billion liters in 2009 to 45.4 billion liters in 2015. Our baseline is approximately 10% higher than the baseline used by the EPA (2010) and roughly 6% lower than the baseline implied by the USDA's 2008 Long Term Agricultural Projections.[35]

The second row of Table 2.2 presents the amount of ethanol added to the economy as a result of the RFS relative to the baseline with the VEETC in place. The RFS does not bind in 2009, hence no ethanol is added to the economy as a result of the RFS. For this reason, in the tables that follow we do not report results for 2009. The RFS binds in the remaining years, forcing additional ethanol in the economy. In 2012, the RFS increases ethanol consumption by 6.1 billion liters. By 2015, the amount of ethanol added as a result of the RFS nearly doubles, reaching 11.4 billion liters. When the RFS is swapped for the VEETC (row three), the amount of ethanol added by the RFS is roughly the same since the RFS binds.

The fourth row of Table 2.2 reports the per liter lifecycle emissions savings of ethanol relative to gasoline, the term $\phi_E + \phi_Y \tilde{A}_Y - \phi_G$, in equation (2.3.19). In 2009, we find that the lifecycle emissions savings of ethanol relative to gasoline is 0.8 $kgCO_2e$/liter. This is

[35] See Appendix section B.7 and Appendix Table B.9.

consistent with other estimates (Farrell et al., 2006; Liska et al., 2009).[36]

The next row reports the *intended emissions savings* of the RFS, the term I from equation (2.3.19), which is the product of the per liter lifecycle emissions savings and the amount of ethanol added by the RFS. In 2012, intended emissions savings of the RFS are 5.1 TgCO$_2$e. Over time, I increases in proportion to the amount of ethanol added by the RFS. By 2015, following the approximate doubling in the amount of ethanol added by the RFS, I nearly doubles to 9.7 TgCO$_2$e. When the RFS binds, the VEETC has no impact on the amount of ethanol in the economy. When the RFS binds, the VEETC has no impact on the amount of ethanol in the economy. As a result, the intended emissions savings of the RFS are unaffected by the renewal or expiration of the VEETC. Below, we compare each leakage source to intended emissions savings by reporting leakage as a percentage of intended emissions savings. While our leakage results may, at first, appear implausible, we note that this is because the intended emissions savings of the RFS are modest because in this calculation the lifecycle estimates of emissions from expanded ethanol and corn production offset a majority of the emissions savings from displaced gasoline.[37]

The second panel in Table 2.2 displays the ethanol added and intended emissions savings due to the RFS relative to a baseline without the VEETC in place. As shown in the first row, baseline ethanol quantities increase from 21.2 billion liters of in 2009 to 31.2 billion liters in 2015 when the VEETC is not in place. Since the baseline without the VEETC is considerably lower than our central baseline that includes the VEETC, the amount of ethanol added by the RFS in this case is larger, with the RFS contributing 25.1 billion liters of ethanol to the economy in 2012 and 25.8 billion liters in 2015 (row 2). As a result, the

[36] Using 2009 values for corn yields and corn-to-ethanol conversion efficiency, the amount of land required for ethanol production, $\tilde{A}_Y$, are 0.19 ha/1000 liters and therefore the lifecycle emissions of corn ethanol, $\phi_E + \phi_Y \tilde{A}_Y$, are 1.17 kgCO$_2$e/liter. Relative to gasoline, ethanol achieves 40% emissions savings after adjusting for the relative energy content of the two fuels. Over time, the lifecycle emissions savings of ethanol increases due to exogenous improvements in corn yields and ethanol production efficiency that are imposed between years of the simulation.

[37] To aid in the interpretation of our results, we note that corn (3.2 mgCO$_2$e/ha) is roughly three times as emissions intensive as the average of the other crops (0.9 mgCO$_2$e/ha), and the conversion of land to agriculture in the rest of the world (8 mgCO$_2$e/ha) is nearly four times more emissions intensive than the conversion of CRP to cropland (2.3 mgCO$_2$e/ha).

main mechanism that our decision to include the VEETC in the baseline will have on our estimates of emissions due to the RFS will be through the amount of ethanol that the RFS adds to the economy. However, the fundamental economic intuition that explains this case is very similar to our central assessment of the RFS when the VEETC is renewed.

2.4.2 Impacts on Land Use

Table 2.3 summarizes the impact of the RFS on domestic and international land use. The first row in the top panel displays the amount of land allocated to corn production in the baseline. In 2012, we predict that 33.9 million hectares of land will be allocated to corn production. The next row reports the amount of additional land allocated to corn production needed to fulfill the mandated expansion in ethanol, 1.1 million hectares in 2012, under the assumptions of LCA (this is $\tilde{A}_Y \frac{dE}{d\theta}$ in equation (2.3.19)). However, as the RFS drives crop prices up, the demand for crops by the food sector and for exports declines, alleviating part of the initial pressure to expand corn production in response to the RFS. Thus, the *actual* change in the amount of land actually allocated to corn production, reported in row three, is only 1.0 million hectares. Similarly, the demand for other crops by the food sector and crop exporters also contracts, leading to a 0.8 million hectare reduction in the amount of land allocated to the production of other crops (row four).

As crop prices rise, the net returns to cropland increase relative to the rental payment received for holding land in CRP, causing an adjustment along the extensive margin. As provided in the fifth row, this adjustment corresponds to 0.3 million hectares of CRP land returning to cropland. The final row reports the impact of the RFS on rest of world land allocated to purposes other than agricultural production. To replace crops previously exported from the U.S., rest of world non-agricultural land (cropland) declines (expands) by 0.5 million hectares in 2012.

Corresponding to the approximate doubling in the amount of ethanol added between 2012 and 2015, land use adjustments also approximately double.[38] For example, the additional

[38]This latter result is largely due to our assumption of constant crop acreage elasticities over time.

land allocated to corn production increases from 1.0 million hectares in 2012, to 2.0 million hectares in 2015.

The effects of swapping the RFS for the VEETC are displayed in the second panel of Table 2.3. As the binding RFS determines the amount of ethanol added to the economy, swapping the VEETC for the RFS has no additional impact on land use or crop prices.[39]

Land Market Leakage

Table 2.4 reports land market leakage a percentage of intended emissions savings. As displayed in the second row, total land market leakage is positive and large in magnitude. *Leakage from the world land market* (presented in row eight) represents the bulk of this effect. Despite being negative, *leakage from the domestic land market* (row three) is negligible in magnitude relative to leakage from the world land market. In 2012, total land market leakage offsets 70.2% of the 5.0 $TgCO_2e$ intended emissions savings, with negative leakage from the domestic land market of 9.4%, only partially offsetting the overwhelmingly positive leakage from the world land market of 79.6%. L^{WA} dominates total land market leakage because the emissions released from bringing one hectare of land into crop production in the rest of the world is emissions intensive (see Table 2.1). While highly uncertain, it is the the potentially large magnitude of leakage from the world land market that caused much of the earlier literature to focus on quantifying this effect (e.g Searchinger et al. (2008) and Hertel et al. (2010)).

Although net domestic land market leakage is small, examining this magnitude in isolation masks the contradictory changes in the domestic land allocation which yields this result. As reported in rows four through six, L^{DA} is negative because negative leakage arising from adjustments within the intensive margin of -14.6%, more than offsets positive leakage arising from adjustments along the extensive margin of 12.3%.[40] That leakage from the domestic land market is negative does not correspond to a reduction in emissions from domestic agri-

[39]See Appendix TableB.12.

[40]To the extent that there are shifts away from livestock production, our framework would actually underestimate the potential for negative leakage due to increased crop and food prices.

culture. On the contrary, as displayed in rows 8 and 9 of Table 2.4, leakage from the domestic land market is negative because the emissions from increased corn production included as intended emissions savings, 3.5 TgCO_2e, actually over account for the change in emissions from the domestic land market, 3.0 TgCO_2e.

In 2015, total land market leakage is again positive, or 85.3% of intended emissions savings of 9.6 TgCO_2e, because positive leakage from the world land market continues to wipe out negative leakage from the domestic land.

Consistent with the findings of Table 2.3, land market leakage resulting from swapping the RFS for the VEETC is identical to land market leakage resulting from the RFS when the VEETC is renewed.

2.4.3 Impacts on Fuel Markets

The impact of the RFS on domestic and world fuel markets are displayed in Table 2.5. We first focus on the impacts on domestic blended fuel consumption, followed with a discussion of the impacts on world crude oil consumption.

The change in blended fuel consumption depends on how the price of blended fuel responds to the RFS, which is reported in row two of Table 2.5. Whether the price of blended fuel decreases as a result of the RFS depends upon whether the price of ethanol increases sufficiently to offset the fall in the price of gasoline. As a simple rule, given that ethanol remains roughly 10% of a liter of blended fuel both before and after the RFS is introduced, for the price of blended fuel to decrease, the percentage increase in the price of ethanol must be no greater than ten times that the percentage decline in the price of gasoline. In 2012, the RFS reduces the price of blended fuel by 0.3% if the VEETC is renewed. This reduction occurs because the increase in the price of ethanol of 10.3% (displayed in row four) is not sufficient to offset the fall in the price of gasoline of 1.3% (row six).

As reported in the eighth row, the fall in the price of blended fuel due to the RFS results in an increase in blended fuel consumption of 0.6 billion liters. In 2015, the price of blended fuel also declines with the RFS, now by 0.4%. The corresponding increase in blended fuel consumption is 1.0 billion liters.

The impact of swapping the RFS for the VEETC on fuel markets is displayed in the lower panel of Table 2.5. Swapping the RFS for the VEETC has a dramatically different impact on fuel markets than the RFS when the VEETC is renewed. Swapping the VEETC for the RFS results in the same change in the producer price of ethanol as the VEETC renewed case. However, the removal of the subsidy results in a greater increase in the price of ethanol faced by fuel blenders, equal to the amount of the eliminated subsidy. Correspondingly, the price of ethanol increases by 51.7% in 2012, which is easily more than ten times the fall in the price of gasoline of 2.0%. Swapping the RFS for the VEETC causes the price of blended fuel to increase 1.3% and the consumption of blended fuel to fall 1.9 billion liters.[41] In 2015, the price of blended fuel increases by 1.2%, which corresponds to a reduction in blended fuel of 1.7 billion liters.

Unlike the price of blended fuel, the RFS unequivocally lowers the world price of crude oil (displayed in the tenth row) regardless as to whether the VEETC is renewed or eliminated. In 2012, the RFS causes the price of crude oil to decline by 1.6% when the VEETC is renewed. In response, rest of world consumption of crude oil increases by 0.7 billion liters (4.4 million barrels). In 2015, when the RFS increases ethanol consumption by roughly 11 billion liters, the reduction in the price of crude oil is 3.1%, and world crude oil consumption increases by 1.4 billion liters (8.8 million barrels).

As illustrated by the lower panel of Table 2.5, swapping the RFS for the VEETC results in a stronger negative impact on the price of crude oil and therefore causes a larger increase in rest of world crude oil consumption. This larger fall in the price of crude oil corresponds to the additional reduction in blended fuel and gasoline that is induced when the RFS is swapped for the VEETC relative to when the VEETC is renewed. In 2012, swapping the

[41] The price of blended fuel equals the price of ethanol, net of VEETC, weighted by the share of ethanol in each liter of blended fuel plus the price of gasoline weighted by the share of gasoline in each liter of blended fuel (energy-equivalence adjusted). Hence, when the VEETC is present in the baseline but is removed when the RFS is imposed, the change in the price of blended fuel reflects the sum of changes in share weighted input prices, plus an additional VEETC term, which further pushes up the price of blended fuel relative to the VEETC inclusive baseline. See Appendix for further discussion.

RFS for the VEETC causes the price of crude oil to fall by -2.6% and rest of world crude oil consumption to increase by 1.1 billion liters (7.2 million barrels). In 2015, this policy change causes world crude oil consumption to increase by 1.9 billion liters (11.8 million barrels).

Fuel Market Leakage

Table 2.6 presents leakage in fuel markets due to the RFS. Total fuel market leakage, reported in the second row, offsets 61.8% of intended emissions savings in 2012. The third and fourth rows decompose total fuel market leakage into *leakage from the domestic fuel market* and *leakage from the world crude oil market*, L^{DF} and L^{WF} from equation (2.3.19). Leakage from the domestic fuel market accounts for approximately two-fifths of total fuel market leakage, or 26.2% of intended emissions savings. Leakage from the world crude oil market is slightly larger at 35.6% of intended emissions savings. In 2015, total fuel market leakage increases slightly to 62.1%, of which domestic fuel market leakage continues to contribute approximately two-fifths. Positive leakage in fuel markets does not imply that emissions from global fuel use increase. In 2015, reductions in domestic gasoline emissions used to calculate intended emissions savings total 22.6 $TgCO_2e$ (fifth row). However, total fuel market leakage is positive because the RFS caused emissions from domestic gasoline and ROW crude to only fall by 16.6 $TgCO_2e$.

When the RFS is swapped for the RFS, total fuel market leakage is negative, following the reversal of the impact on blended fuel consumption. In 2012, total fuel market leakage is negative and strikingly large, -66.5% of intended emissions savings. In effect, fuel market adjustments from swapping the RFS for the VEETC generate additional emissions reductions that are about two-thirds the magnitude of the intended emissions savings. Due to the large reduction in blended fuel consumption when the RFS is swapped for the VEETC, negative leakage from domestic fuel adjustments is 127.0% of intended emissions savings and only a portion of this negative leakage is offset by positive leakage from the world crude oil market. Consistent with the larger expansion in world crude oil consumption when domestic blended fuel consumption contracts, leakage from the world crude market is 60.5% of intended emissions savings.

In 2015, total fuel market leakage remains negative, but is of a considerably smaller magnitude, only -6.8% of intended emissions savings. Here, negative leakage from the domestic fuel market is 57.5% of intended emissions savings, while positive leakage from the world crude oil market offsets 50.7%. This decline in negative leakage from the domestic fuel market is a result of both the decreasing reduction in blended fuel consumption and the doubling of intended emissions savings between 2012 and 2015.

It is clear from Table 2.6 that leakage from the domestic fuel market exhibits considerable variability in both direction and magnitude. This is because the per liter emissions from gasoline are on the order of three times greater than the intended emissions savings of an energy equivalent quantity of ethanol (see Appendix Table B.7). As a result, leakage from domestic fuel markets proves to have a critical impact on the estimated emissions savings of the RFS. This is a key result of this paper, providing clear evidence for the need to carefully integrate both fuel and land markets in order to properly assess the emissions consequences of biofuel policies.

2.4.4 Will the RFS Reduce Emissions?

Table 2.7 decomposes, for the years 2010, 2012 and 2015, the net change in emissions due to the RFS into intended emissions savings and leakage, and breaks down total leakage into land and fuel market leakage following the analysis in Tables 2.4 and 2.6. Figure 2.1 graphically depicts these results for each year from 2010 to 2015. The first panel in Figure 2.1 illustrates how the overall change in emissions due to the RFS evolves as the amount of ethanol added by the RFS expands over time. The horizontal axis measures the quantity of ethanol added by the RFS for each year that the RFS binds, 2010 through 2015, relative to a baseline in which the VEETC is renewed. The vertical axis measures the resulting change in emissions.

The overall change in GHG emissions is depicted by the black line. Our central finding is that the RFS will increase GHG emissions relative to a baseline with the VEETC in place. Further, the increase in overall emissions becomes larger as the RFS mandates larger amounts of ethanol. In 2010, for an additional 3.7 billion liters of ethanol the RFS causes emissions to increase by 0.4 $TgCO_2e$ (Table 2.7). By 2015 the RFS causes ethanol to expand by 11.4 billion liters, corresponding to an emissions increase of 4.5 $TgCO_2e$.

The three gray lines decompose the overall change in emissions into intended emissions savings, land market leakage and fuel market leakage. Intended emissions savings (labeled "Intended") exhibits a clear negative linear relationship with the ethanol added by the RFS. Intended emissions savings are 3.0 $TgCO_2e$ in 2010 and expand dramatically to 9.7 $TgCO_2e$ in 2015.

The line labeled "Intended + Land Market Leakage" depicts the sum of intended emissions savings and land market leakage. Thus, the vertical distance between this line and the intended emissions savings line represents net land market leakage, which is positive in each year. In 2010, if land market leakage is considered along with intended emissions savings, the RFS would only reduce emissions by 1.7 $TgCO_2e$, which is considerably less than intended emissions savings calculated using lifecycle methods. By 2015, despite intended emissions savings expanding greatly, emissions savings net of land market leakage falls to 1.5 $TgCO_2e$. This highlights that per liter of ethanol added by the RFS, land market leakage increases with the quantity of ethanol added by the RFS.[42] Domestic land supply is convex in the amount of corn land added by new ethanol due to the RFS, since corn yields are declining in the amount of acres under cultivation. Thus each marginal liter of ethanol added by the RFS to have a larger impact on crop prices. As domestic land supply tightens, the contraction in crops demanded by the food sector and crop exporters becomes more severe, magnifying each of source of land market leakage, particularly leakage from the world land market. Interestingly, this occurs despite crop yields and ethanol conversion efficiency improvements over time, which relieves some of this pressure.

The line labeled "Intended + Fuel Market Leakage" depicts the sum of intended emissions savings and fuel market leakage. This line falls above the intended emissions savings line

[42] As reported in Appendix Table B.13 land market leakage increases from 0.34 $kgCO_2e$ per liter additional ethanol in 2010 to 0.72 $kgCO_2e$ per liter in 2015.

because fuel market leakage due to the RFS is consistently positive when the VEETC is renewed. Intended emissions savings net of fuel market leakage is only 0.9 $TgCO_2e$ in 2010, but increases to 3.7 $TgCO_2e$ by 2015. Unlike land market leakage, fuel market leakage per liter of ethanol added by the RFS is roughly constant between 2010 and 2015 (see Appendix Table B.13).[43]

These results emphasize the importance of considering both land and fuel market leakage in a unified and consistent manner. Further, given that neither land nor fuel market leakage is sufficient to completely offset intended emissions savings, considering either source of leakage independently would result in a misleading conclusion that the RFS reduces emissions. In contrast, we find that the RFS unambiguously increases emissions.

The second panel in Figure 2.1 presents the same decomposition of GHG emissions as the first panel, when the RFS is swapped for the VEETC. Unlike the RFS when the VEETC is renewed, replacing the VEETC with the RFS can result in emissions reductions. In these two cases intended emissions savings and land market leakage are roughly identical, which is illustrated by the lines "Intended" and "Intended + Land Market Leakage" in the top two panels. In sharp contrast, swapping the RFS for the VEETC results in negative fuel market leakage, which is illustrated by the "Intended + Fuel Market Leakage" line falling below "Intended" line in each year.

In 2010, negative fuel market leakage dominates positive land market leakage. Thus, the overall reduction in emissions due to the RFS, 5.4 $TgCO_2e$, is greater than intended emissions savings of 2.8 $TgCO_2e$. In 2013 and after, the overall change in emissions, while still negative, is less then intended emissions savings. For example, in 2015 there is a net reduction in emissions of 2.0 $TgCO_2e$, while intended emissions savings are 9.5 $TgCO_2e$.

[43]Per liter ethanol, total fuel market leakage remains constant over time because leakage from the domestic fuel market becomes less intensive offsetting intensification in leakage from the world crude market. The total increase in blended fuel, and leakage from the domestic fuel market, is roughly constant as more ethanol is added by the RFS because the increase in the price of ethanol remains in rough proportion to the fall in the price of gasoline. In contrast, leakage from the world crude oil market intensifies slightly because the excess supply of crude oil is convex, resulting in a larger reduction in the world price of crude oil for each additional liter of ethanol added by the RFS.

Although net fuel market leakage is negative for each of the ethanol volumes added by the RFS over time, it is declining in magnitude. This is illustrated by the vertical distance between the "Intended" and "Intended + Fuel Market Leakage" lines shrinking as the amount of ethanol added by the RFS expands. The impact of swapping the RFS for the VEETC on the price and quantity of blended fuel, and therefore the magnitude of leakage from the domestic fuel market, is roughly constant in each year. However, the same economic adjustments that result in negative domestic fuel market leakage, also imply world fuel market leakage to be larger at the margin. More gasoline displaced domestically corresponds to greater marginal world fuel market leakage, eroding the negative leakage from the domestic fuel market.. This suggests that studies that ignore leakage from fuel markets and interactions with pre-existing policies, such as the VEETC, will likely incorrectly estimate total leakage. Perhaps even more importantly, such studies could potentially miss the direction of the total change in emissions.

Swapping the VEETC with the RFS reduces emissions in each year, although this emissions reduction is contingent on the elevated level of emissions in the VEETC baseline. Thus, relative to the pre-2006 policy regime in which the VEETC was the dominant biofuel policy, the post-2011 policy regime in which just the RFS is the dominant biofuel policy implies more ethanol added to the economy and considerably fewer GHG emissions. The third panel of Figure 2.1 plots the overall change in emissions due to the RFS when the VEETC is renewed and when the VEETC is replaced by the RFS (the black lines from panels 1 and 2), as well as intended emissions savings. This graphically demonstrates the emissions implications of the decision to allow the VEETC to expire conditional on a binding RFS. Swapping the RFS for the VEETC leads to a parallel downward shift in the overall emissions curve. The resulting emissions savings are 6.5 $TgCO_2e$ in 2015, and slightly lower for earlier years. This suggests that the decision to allow the VEETC to expire at the end of 2011 will have resulted in cumulative emissions savings of 25.5 $TgCO_2e$ by 2015.[44]

[44]The reduction in emissions identified here should not be attributed to imposing just the RFS or eliminating just the VEETC. Rather it corresponds to the emissions savings achieved from eliminating the VEETC

Limits to Emissions Savings From Swapping RFS for VEETC

The third panel of Figure 2.1 also suggests that there are limits for the switch in policy regimes from VEETC to RFS to achieve both an increase in ethanol and a reduction in emissions. If, as some policymakers have recently suggested, the conventional RFS was expanded to compensate for the inability of the U.S. to meet the advanced RFS, there will likely be mandated volumes of corn ethanol for which emissions will increase. A simple extrapolation of the overall emissions curve suggests that replacing the RFS with the VEETC will start to increase overall emissions when more than 15.6 billion liters of ethanol are added by the RFS. After this point, replacing the VEETC with the RFS will imply a fundamental trade-off between ethanol expansion and increased emissions.

2.4.5 Impacts of Eliminating the RFS Now that the VEETC Has Expired

As discussed earlier, the RFS Elimination Act has proposed eliminating the RFS for conventional biofuels. Given that the VEETC has expired, elimination of the RFS at this point will entail moving to a regime where there is no large-scale support program in place for corn ethanol. Table 2.8 presents the change in ethanol, intended emissions savings and leakage due to the RFS relative to a baseline that does not include the VEETC for the years 2010, 2012 and 2015. Examination of this case suggests the implications from moving from the current, post-2011 regime in which just the RFS is in place to a new regime where the RFS has been eliminated and the VEETC is not resurrected.

Relative to the no-VEETC baseline, the RFS results in greater GHG emissions. In 2010, the RFS causes ethanol to increase by 23.0 billion liters and emissions to increase by 6.8 $TgCO_2e$. By 2015 the RFS causes ethanol to expand by 25.8 billion liters, corresponding to an emissions increase of 6.7 $TgCO_2e$. Consequently, eliminating the RFS would provide a modest emissions reduction.

The increase in emissions in this case are larger than those of the RFS relative to the

conditional on the RFS binding.

baseline that includes the VEETC, when the VEETC is renewed, mostly because the RFS has a considerably larger impact on ethanol. However, leakage and the net change in emissions are not proportional to the change in ethanol quantities. Appendix Table B.15 reports the emissions impacts per liter of ethanol added by the RFS relative to the no-VEETC baseline. The corresponding results for the RFS relative to the VEETC baseline are reported in Appendix Table B.13. Per liter of ethanol added by the RFS in 2015, land market leakage is greater when the RFS is compared to the VEETC baseline (0.72 $kgCO_2e$/liter) than when the RFS is compared to the baseline without VEETC (0.55 $kgCO_2e$/liter). Conversely, fuel market leakage per liter of ethanol added by the RFS is smaller when comparing to the VEETC baseline, 0.53 $kgCO_2e$/liter, than when comparing to the no VEETC baseline, 0.58 $kgCO_2e$/liter. These two observations illustrate the critical manner in which land market and fuel market leakage are jointly determined, and that leakage in both markets will depend on the choice of baseline.

The baseline quantity of ethanol, and therefore corn, is lower in the no-VEETC baseline. Since the RFS adds ethanol to a slacker land market in this instance, land market leakage per liter of ethanol added is smaller in this case. In contrast, the VEETC in the baseline serves to elevate the amount of ethanol and corn in the baseline, so that the additional ethanol added by the RFS relative to this baseline corresponds to larger impacts on crop prices and land market leakage at the margin. The same economic forces that drive this differential land market leakage at the margin also correspond to a larger increase in the price of ethanol and thus a smaller decrease in the price of blended fuel at the margin. As a result, domestic fuel market leakage per liter of ethanol added by the RFS is smaller when evaluating the RFS relative to a baseline that includes the VEETC than when assessing the RFS relative to the baseline without the VEETC.

The same increase in corn prices that affects land market leakage at the margin also translates into a greater increase in the price of ethanol and a smaller decrease in the price of blended fuel at the margin. As a result, domestic fuel market leakage is smaller for the

VEETC renewed case than when assessing the impact of the RFS relative to the baseline without the VEETC.

2.4.6 Benefits of a Unified Framework of Land and Fuel Markets

A common approach in the literature (Thompson et al., 2011; Rajagopal and Plevin, 2013) has been to evaluate the implications of biofuel policies assuming constant land market adjustments and/or emissions factors. While direct comparisons to the literature are difficult due to differences in policies being examined, time-horizon of evaluation as well as other modeling assumptions, we can get at the implications of this assumption in the context of our own analysis which allows us to hold such assumptions fixed. For example, we can re-evaluate the emissions savings of the RFS relative to a baseline in which the VEETC is in place, by imposing the per liter land market leakage implied by our analysis of the RFS relative to a baseline without the VEETC, and vice-versa. Doing so would imply that per liter emissions due to the RFS would fall from 0.40 to 0.23 kgCO_2e/liter for the case when the VEETC is included in the baseline. Thus, the RFS would increase emissions by 41.8% less than our central result. In contrast, performing the same analysis in reverse for the RFS relative to the baseline without the VEETC results in a total change in emissions due to the RFS that is 63.6% larger than our central result. Although this analysis relies on a simple back of the envelope calculation, it demonstrates how differences in policy regime can affect average land market leakage and highlights limitations of many prior analyses.

2.4.7 Sensitivity Analysis

We perform a comprehensive sensitivity analysis of the emissions impacts of the RFS for conventional biofuels for our two central policy regimes. Table 2.9 reports the impact of the RFS on emissions by varying two alternative sets of parameters that primarily impact adjustments in fuel markets: the elasticity of excess supply of crude oil and the elasticities of demand for blended fuel and VMT with respect to the price of fuel. Table 2.10 evaluates the implications of varying two sets of parameters that primarily affect adjustments in land markets: the elasticities of crop demand for domestic food production and the agricultural and land use emissions factors. Both tables focus exclusively on 2015, report the baseline amount of ethanol, the change in ethanol induced by the RFS, emissions and leakage terms per liter of ethanol added by the RFS. Details on the parameter cases being varied are provided at the bottom of each table. To ease comparison, we re-state the emissions outcomes for the central parameter assumptions in the first column in both tables. For the sake of brevity, we emphasize the results from varying the blended fuel and VMT elasticities from Table 2.9 and the elasticities of crop demand for food production from Table 2.10. Additional results for these cases in 2012 are provided in Appendix Tables B.16 and B.17. Appendix Table B.18 reports sensitivity analysis that varies the energy and corn requirements of ethanol production, in light of research suggesting that the efficiency and lifecycle emissions of ethanol production has been improving over time (Liska et al., 2009).

More elastic fuel and VMT demand imply larger increases in emissions for the RFS when the VEETC is renewed, but larger reductions in emissions when the RFS replaces the VEETC.[45] This result arises because both demand for VMT and blended fuel are more responsive to changes in the price of blended fuel. Consequently, both the fall in the price of blended fuel due to the RFS when the VEETC is renewed and the increase in the price of blended fuel that results when the RFS replaces the VEETC are larger. This increases the magnitude of domestic fuel market leakage in both cases although it has no impact on the direction of leakage. Land market leakage is relatively unaffected by changes in the elasticities of fuel and VMT demand because the RFS sets the level of ethanol in the economy, which causes corn to increase by a fixed quantity.

Increasing the elasticities of crop demand for domestic food production implies a smaller increase in crop prices as a result of the RFS.[46] This increases the magnitude of negative

[45]The high case jointly increases the elasticities of blended fuel and VMT demand by 0.1 from their central values of 0.3 and 0.2, respectively, whereas the low case considers a joint decrease in both elasticities by 0.1. This is achieved by modifying the elasticities of substitution, σ_U, σ_W, and σ_M in equation (B.2.1) as provided in the Appendix.

[46]The low and high cases are constructed by halving and doubling the elasticities of substitution, σ_X, σ_Q and σ_V, as provided in equation (B.2.10) in the Appendix.

domestic land market leakage and decreases the magnitude of positive leakage from the world land market, resulting in lower land market leakage overall. In addition, increasing these elasticities causes the residual supply of corn available for ethanol production (e.g. total corn supply less corn demanded by exporters and domestic food producers) to become more elastic. Therefore, the increase in the price of ethanol due to the RFS is softened, implying a larger fall in the price of blended fuel for the RFS when the VEETC is renewed and a smaller decrease in the price of blended fuel when the RFS is swapped for the VEETC. Accordingly, positive domestic fuel market leakage increases in magnitude for the former, but negative domestic fuel market leakage declines in magnitude for the latter. However, world fuel market leakage decreases in magnitude for both. Cumulatively, more elastic crop demand implies a smaller increase in emissions due to the RFS when the VEETC is renewed and a larger reduction in emissions when the RFS replaces the VEETC.[47]

Comparing the results of these two analyses provides a very illuminating insight regarding the mechanisms through both land and fuel market leakage are co-determined. Varying parameters that impact primarily fuel markets, such as varying the elasticities of fuel and VMT demand, implies little change in land market leakage largely because blended fuel is not an input in crop production. The only extent that land market leakage is affected when we vary fuel market parameters is when adjusting these parameters impacts the ethanol baseline. In this case land market leakage is marginally affected owing principally to our earlier observation regarding the addition of ethanol to ever tighter land markets. In sharp contrast, varying parameters that primarily impact land markets, such as the elasticities of crop demand for domestic food production, impacts both land and fuel market leakage because these parameters directly impact the equilibrium price of corn which is effectively an input in the production of blended fuel.

[47]The crop demand elasticities for domestic food production also have a significant impact on the baseline quantity of ethanol in 2015. As a result, some of the leakage values per liter ethanol added do not follow expected patterns because the quantity of ethanol added by the RFS vary across sensitivity runs.

Bounds of Emissions Results

Although not reported here, we explored emissions results under all 81 combinations of the four sets of sensitivity assumptions. Emissions increase in 63 out of 81 cases (78%) when the VEETC is renewed, which suggests our central finding that the RFS causes emissions to increase is robust. When the RFS is swapped for the VEETC, emissions decrease in 48 out of 81 cases (59%), which suggests that our central result that swapping the VEETC with the RFS will result in fewer emissions is not nearly as robust.[48] Table 2.11 reports the best and worst cases for the change in emissions per liter of ethanol added across all 81 parameter combinations in 2015.[49] When the VEETC is renewed, the RFS reduces emissions by 0.32 kgCO_2e per liter of ethanol added in the best case, but increases emissions by 2.01 kgCO_2e per liter of ethanol added in the worst case. The worst case is a five-fold increase over the central results. When the RFS is swapped for the VEETC, the reduction in emissions is at best 1.36 kgCO_2e per liter of ethanol added, a six-fold greater decline in emissions than our central result for this case. At worst, net emissions increase by 1.62 kgCO_2e per liter of ethanol added.[50]

2.5 Conclusion

This paper developed a multi-market economic model that integrates fuel, land and food markets and is linked with a disaggregated emissions model to examine the effects of the

[48]In 2012 we find that the RFS will increase emissions under 61 parameter combinations if the VEETC is renewed. Swapping the VEETC with the RFS, however, will reduce emissions for 65 parameter combinations. This is because the land market leakage and world fuel market leakage is substantially smaller in 2012 compared to 2015, while domestic fuel market leakage is of the same gross magnitude.

[49]The best case uses the high elasticity of crude oil supply, the high crop demand elasticities for domestic food production and the low agricultural and land use emissions, both for the RFS when the VEETC is renewed and when the RFS is swapped for the VEETC. Since varying the fuel and VMT elasticities cause the total change in emissions due to the RFS to move in opposite directions depending the policy context being considered, low elasticities of fuel and VMT demand are used for the RFS when the VEETC is renewed and high values are used for these elasticities when the RFS is swapped for the VEETC. The worst case is the reverse of these parameter combinations.

[50]Although not reported for space considerations, we conduct an identical sensitivity analysis for the RFS relative to a baseline without the VEETC. In 2015, we find that the RFS increases emissions in 58 of the 81 parameter cases (71%) in 2015. The emissions impacts per liter ethanol added by the RFS range from a decrease of 0.47 kgCO_2e/liter to an increase of 1.72 kgCO_2e/liter.

RFS for conventional biofuels on GHG emissions. The framework allows for both positive and negative leakage to arise from changes in policy regimes. These features are crucial for evaluating incomplete climate legislation because interactions between policies resulting from changes in policy regimes can impact the magnitude and direction of leakage.

Our central finding is that the expansion of biofuels mandated by the RFS can increase or decrease GHG emissions depending on the policy regime being evaluated. Relative to a baseline that includes the VEETC, which was in place when the current RFS was established, the RFS causes emissions to increase by 4.5 $TgCO_2e$ in 2015. However, swapping the RFS for the VEETC implies fewer GHG emissions than those that result from the VEETC itself, causing emissions to fall by 2.0 $TgCO_2e$ in 2015. Thus, the decision to allow the VEETC to expire at the end of 2011 will result in cumulative emissions savings of 25.5 $TgCO_2e$ between 2012 and 2015, while increasing ethanol production considerably. Finally, the RFS causes emissions to increase by 6.7 $TgCO_2e$ in 2015 when evaluated relative to a baseline without the VEETC. Given that the VEETC has expired, this is also the amount by which emissions could be reduced if the RFS for conventional biofuels was eliminated, although a full cost-benefit analysis, along the lines of Chen et al. (2011), Lapan and Moschini (2012) or Landry and Bento (2013), would be needed before making such a significant policy change.

While the overall impact on emissions of the policy regimes we consider are modest, our numerical analysis uncovers two surprising results that could not be inferred from a theoretical exercise, an analysis of a single market alone, or a multi-market analysis that uses constant emissions factors in one of the markets. First, both baselines and policy context matter when determining the change in overall GHG emissions and the contributions of each leakage channel. The RFS alone increases emissions relative to both a baseline that includes the VEETC and a baseline that does not include the VEETC. However, per liter of ethanol added by the RFS, land market leakage is smaller and fuel market leakage greater when assessing the impact of the RFS relative to a no-VEETC baseline than when performing the same analysis in relation of a baseline that includes the VEETC. Critically, this reveals how emissions from one leakage channel are co-determined with emissions from another leakage channel through linked markets. The difference between the two cases results from the impact of the VEETC on the baseline, with the RFS causing less ethanol to be added to a tighter market when comparing to a baseline that includes the VEETC then when comparing to a baseline without the VEETC. Relatedly, swapping the RFS for the VEETC implies fewer GHG emissions than those that result from the VEETC alone, which illustrates that pre-existing policies can lead to reversals in the direction of leakage and the overall change in GHG emissions.

Second, we show that there is an implicit tension between land and fuel market leakage channels. Policy regimes that result in less land market leakage tend to result in more domestic fuel market leakage per liter of ethanol added. Likewise, sensitivity analysis on the elasticity of crop demand for food production illustrates that assumptions regarding economic responses that will dampen land market leakage can exacerbate fuel market leakage. This tension reaffirms that the leakage channels are co-determined and that jointly modeling land and fuel markets is critical to understanding the emissions impact of the RFS. The relationship between land and fuel market leakage has important implications for policy since it suggests that due to price effects, different types of policy instruments may lead to different leakage magnitudes. Therefore, this tension should be considered when evaluating other policies that support biofuels.

An important caveat concerns our numerical results. Our simple treatment of the rest of the world, which was necessary for simplicity and tractability, may limit our ability to precisely quantify leakage from the world land and crude oil markets. Quantifying the world land use impacts of U.S. biofuel policies remains a first-order research priority, but is not the purpose of this paper. Analyses that rely on global equilibrium models have generated a wide range of estimates (EPA, 2010; Hertel et al., 2010; Searchinger et al., 2008; Dumortier et al., 2011). This points to the need for more detailed country or regional analyses in the style of Barr et al. (2011). Our estimates of world land use change resulting from expanded biofuels production in the U.S. fall centrally in the range of these published estimates and our main results hold under a range of parameter assumptions. We recognize that our framework does not explicitly model the demand for crude products other than gasoline consumed in the U.S. or any substitutes for crude oil products, and does not account directly for the complexities of the crude oil market, such as potential market power of crude oil suppliers or refineries.

Moving forward, policymakers are considering advanced biofuels and other incomplete climate legislation, such as renewable portfolio standards. Broadly speaking, our findings imply that, the sources of leakage identified here are likely to be present in such proposals, compromising their ability to reduce GHG emissions.

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Table 2.1: Key Central Elasticity Values and Emissions Factors

	Central Value
Key Elasticities	
Blended Fuel Demand	-0.34
Food Demand	-0.12
Corn Supply (area)	0.29
Other Crops Supply wrt to Corn Price	-0.12
CRP wrt to Net Returns to Cropland	-0.07
Corn Export Demand	-0.65
Other Crops Export Demand	-0.59
Crude Oil Excess Supply	0.5

Table 2.2: Ethanol Added and Intended Emissions Savings due to RFS

	2009	2012	2015
Ethanol Baseline, with VEETC (billion liters)	40.1	43.9	45.4
Change in Ethanol Due to RFS (VEETC Renewed)	0.0	6.1	11.4
Change in Ethanol Due to RFS (VEETC Swapped)	0.0	5.8	11.1
Lifecycle Emissions Savings of Ethanol (kgCO_2e/liter)	0.80	0.82	0.84
Intended Emissions Savings, I (TgCO_2e)			
Savings Due to RFS (VEETC Renewed)	0.0	5.1	9.7
Savings Due to RFS (VEETC Swapped)	0.0	4.8	9.5
Ethanol Baseline, no VEETC (billion liters)	21.2	24.5	31.2
Change in Ethanol due to RFS	18.8	25.8	25.8
Lifecycle Emissions Savings of Ethanol (kgCO_2e/liter)	0.83	0.86	0.87
Intended Emissions Savings, I (TgCO_2e)	15.7	22.1	22.4

Notes: Baseline reported is inclusive of the VEETC.

Table 2.3: Impact of RFS on Domestic and International Land Use

	2012	2015
RFS (VEETC Renewed)		
Domestic Corn Baseline (million ha)	33.9	33.4
Additional Corn Required	1.1	2.0
Change in Domestic Corn	1.0	2.0
From Other Crops	-0.8	-1.4
From Land Held in CRP	-0.3	-0.5
Change in World Non-Agricultural Land	-0.5	-1.1
RFS (VEETC Swapped)		
Domestic Corn Baseline (million ha)	33.9	33.3
Additional Corn Required	1.1	1.9
Change in Domestic Corn	1.0	1.9
From Other Crops	-0.8	-1.4
From Land Held in CRP	-0.3	-0.5
Change in World Non-Agricultural Land	-0.5	-1.1

Notes: Baselines reported are inclusive of the VEETC. "Additional Corn Required" is the amount of land needed to produce the ethanol added by the RFS. "Other crops" includes soybeans, wheat, hay and cotton.

Table 2.4: Land Market Leakage from RFS

	2012	2015
RFS (VEETC Renewed)		
Intended Emissions Savings, I ($TgCO_2e$)	5.0	9.7
Total Land Market Leakage	70.2%	84.4%
Leakage From the Domestic Land Market, L^{DA}	-9.4%	-8.4%
From Changes in Food and Export Demand, L^{Y}	-7.1%	-6.5%
From the Intensive Margin of Land Use, L^{Z}	-14.6%	-14.4%
From the Extensive Margin of Land Use, L^{N}	12.3%	12.5%
Leakage From the World Land Market, L^{WA}	79.6%	92.8%
Change in Corn Emissions in Intended ($TgCO_2e$)	3.5	6.3
Change in Emissions from Domestic Land Market ($TgCO_2e$)	3.0	5.5
RFS (VEETC Swapped)		
Intended Emissions Savings, I ($TgCO_2e$)	4.8	9.5
Total Land Market Leakage	71.6%	85.6%
Leakage From the Domestic Land Market, L^{DA}	-9.2%	-8.3%
From Changes in Food and Export Demand L^{Y}	-6.9%	-6.4%
From the Intensive Margin of Land Use L^{Z}	-14.7%	-14.4%
From the Extensive Margin of Land Use L^{N}	12.4%	12.5%
Leakage From the World Land Market, L^{WA}	80.8%	93.9%
Change in Corn Emissions in Intended ($TgCO_2e$)	3.3	6.1
Change in Emissions from Domestic Land Market ($TgCO_2e$)	2.9	5.3

Notes: All leakage values are reported as a percentage of intended emissions savings, I. Emissions from the domestic land market includes emissions from crop production and the domestic conversion of land to cropland.

Table 2.5: Impact of RFS on Fuel Markets

	2012	2015
RFS (VEETC Renewed)		
Baseline Blended Fuel Price ($/liter)	0.60	0.64
Change in Price of Blended Fuel	-0.3%	-0.4%
Baseline Ethanol Price ($/liter)	0.28	0.31
Change in Price of Ethanol	10.3%	20.5%
Baseline Gasoline Price ($/liter)	0.42	0.46
Change in Price of Gasoline	-1.3%	-2.5%
Baseline Blended Fuel (billion liters)	472.4	472.8
Change in Blended Fuel	0.6	1.0
Baseline Crude Oil Price ($/liter)	0.44	0.50
Change in Crude Oil Price	-1.6%	-3.1%
Baseline World Crude Oil (billion liters)	2,139.0	2,219.7
Change in World Crude Oil	0.7	1.4
RFS (VEETC Swapped)		
Baseline Blended Fuel Price($/liter)	0.60	0.64
Change in Price of Blended Fuel	1.3%	1.2%
Baseline Ethanol Price ($/liter)	0.28	0.31
Change in Price of Ethanol	51.7%	58.5%
Baseline Gasoline Price ($/liter)	0.42	0.46
Change in Price of Gasoline	-2.0%	-3.3%
Baseline Blended Fuel (billion liters)	472.4	472.9
Change in Blended Fuel	-1.9	-1.7
Baseline Crude Oil Price ($/liter)	0.44	0.50
Change in Crude Oil Price	-2.6%	-4.2%
Baseline World Crude Oil (billion liters)	2,139.0	2,219.7
Change in World Crude Oil	1.1	1.8

Notes: Baselines reported are inclusive of the VEETC. Price of ethanol includes the VEETC and price of blended fuel reported is inclusive of a pre-existing fuel tax of 0.10 $/liter. World crude oil reported here includes only the components of the world crude oil market from which we calculate emissions from: crude oil used to produce gasoline in the rest of the world, and crude oil used to produced distillate fuels in the US and the rest of the world. See discussion in the Appendix.

Table 2.6: Fuel Market Leakage from RFS

	2012	2015
RFS (VEETC Renewed)		
Intended Emissions Savings, I ($TgCO_2e$)	5.0	9.7
Total Fuel Market Leakage	61.8%	62.1%
From the Domestic Fuel Market, L^{DF}	26.2%	25.3%
From the World Crude Oil Market, L^{WF}	35.6%	36.7%
Reduction in Gasoline Emissions in Intended ($TgCO_2e$)	12.0	22.6
Reduction in Total Fuel Market Emissions ($TgCO_2e$)	8.9	16.6
RFS (VEETC Swapped)		
Intended Emissions Savings, I ($TgCO_2e$)	4.8	9.5
Total Fuel Market Leakage	-66.5%	-6.8%
From the Domestic Fuel Market, L^{DF}	-127.0%	-57.5%
From the World Crude Oil Market, L^{WF}	60.5%	50.7%
Reduction in Gasoline Emissions in Intended ($TgCO_2e$)	11.5	22.0
Reduction in Total Fuel Market Emissions ($TgCO_2e$)	14.7	22.6

Notes: All leakage values are reported as a percentage of intended emissions savings, I. Total fuel market emissions include emissions from domestic fuel and crude oil in the rest of the world.

Table 2.7: Total Leakage from RFS

	2010	2012	2015
RFS (VEETC Renewed)			
Net Change in Emissions, $dGHG$	0.4	1.6	4.5
Intended Savings, I	3.0	5.0	9.7
Total Leakage	3.4	6.7	14.2
Total Land Market Leakage	1.3	3.5	8.2
Total Fuel Market Leakage	2.1	3.1	6.0
RFS (VEETC Swapped)			
Net Change in Emissions, $dGHG$	-5.4	-4.6	-2.0
Intended Savings, I	2.8	4.8	9.5
Total Leakage	-2.6	0.2	7.5
Total Land Market Leakage	1.2	3.5	8.1
Total Fuel Market Leakage	-3.8	-3.2	-0.6

Notes: All emissions categories are reported in $TgCO_2e$.

Table 2.8: Total Leakage from RFS Relative to No-VEETC Baseline

	2010	2012	2015
Ethanol Baseline, No VEETC (billion liters)	22.7	24.5	31.2
Change in Ethanol due to RFS	23.0	25.8	25.8
Net Change in Emissions (TgCO2e), $dGHG$	6.8	7.0	6.7
Intended Savings, I	19.3	22.1	22.4
Total Leakage	26.1	29.1	29.1
Total Land Market Leakage	12.5	14.0	14.3
Total Fuel Market Leakage	13.6	15.1	14.9

Table 2.9: Emissions in 2015 Under Alternative Parameter Assumptions, Fuel Markets

Crude Oil Excess Supply Elasticity Fuel and VMT Elasticity of Demand	Central Central	Low Central	High Central	Central Low	Central High
RFS (VEETC Renewed)					
Baseline Ethanol Consumption (billion liters)	45.4	46.8	44.7	46.4	44.4
Change in Ethanol Consumption	11.4	10.2	12.0	10.3	12.5
Net Change in Emissions (kgCO_2e per liter ethanol added)	0.40	0.79	0.22	0.34	0.44
Intended Savings, I	0.85	0.85	0.85	0.85	0.85
Domestic Land Market Leakage, L^{DA}	-0.07	-0.05	-0.08	-0.07	-0.08
World Land Market Leakage , L^{WA}	0.79	0.80	0.79	0.80	0.78
Domestic Fuel Market Leakage, L^{DF}	0.22	0.64	0.02	0.14	0.28
World Fuel Market Leakage, L^{WF}	0.31	0.25	0.34	0.32	0.31
RFS (VEETC Swapped)					
Baseline Ethanol Consumption (billion liters)	45.4	46.8	44.7	46.4	44.4
Change in Ethanol Consumption	11.1	9.9	11.7	10.1	12.0
Net Change in Emissions (kgCO_2e per liter ethanol added)	-0.18	0.28	-0.38	-0.11	-0.24
Intended Savings, I	0.85	0.85	0.85	0.85	0.85
Domestic Land Market Leakage, L^{DA}	-0.07	-0.05	-0.08	-0.06	-0.07
World Land Market Leakage , L^{WA}	0.80	0.81	0.79	0.81	0.79
Domestic Fuel Market Leakage, L^{DF}	-0.49	0.02	-0.72	-0.42	-0.56
World Fuel Market Leakage, L^{WF}	0.43	0.35	0.47	0.41	0.45

Notes: Elasticity of crude oil excess supply is 0.25, 0.5 and 0.75 in the low, central and high cases respectively. The elasticity of world crude oil demand is -0.01, -0.02 and -0.03 in the low, central and high cases respectively. Fuel and VMT elasticities of demand are varied by jointly modifying the elasticities of substitution, σ_U, σ_W, and σ_M in equations (B.2.1). The high case increases the elasticities of blended fuel and VMT demand by 0.1 from their central values whereas the low case considers a joint decrease in both elasticities by 0.1.

Table 2.10: Emissions in 2015 Under Alternative Parameter Assumptions, Land Markets

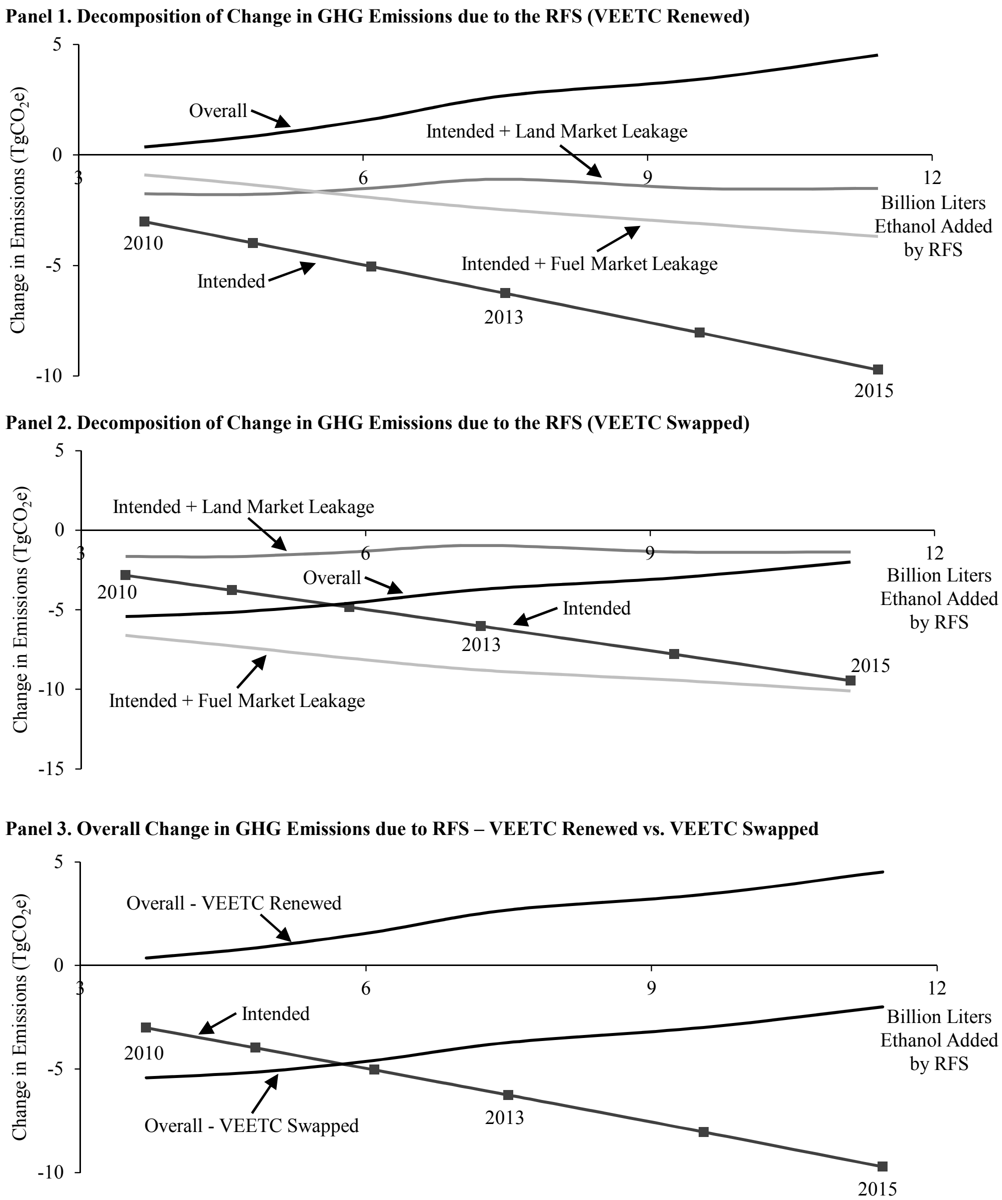
Elasticities of Crop Demand for Food Production Agriculture and Land Use Emissions	Central Central	Low Central	High Central	Central Low	Central High
RFS (VEETC Renewed)					
Baseline Ethanol Consumption (billion liters)	45.4	43.2	49.7	45.4	45.4
Change in Ethanol Consumption	11.4	13.6	7.1	11.4	11.4
Net Change in Emissions (kgCO_2e per liter ethanol added)	0.40	0.51	0.27	-0.09	1.32
Intended Savings, I	0.85	0.85	0.85	0.90	0.43
Domestic Land Market Leakage, L^{DA}	-0.07	0.03	-0.20	-0.18	-0.02
World Land Market Leakage , L^{WA}	0.79	0.88	0.72	0.46	1.24
Domestic Fuel Market Leakage, L^{DF}	0.22	0.12	0.30	0.22	0.22
World Fuel Market Leakage, L^{WF}	0.31	0.33	0.30	0.31	0.31
RFS (VEETC Swapped)					
Baseline Ethanol Consumption (billion liters)	45.4	43.2	49.7	45.4	45.4
Change in Ethanol Consumption	11.1	13.2	6.7	11.1	11.1
Net Change in Emissions (kgCO_2e per liter ethanol added)	-0.18	0.03	-0.68	-0.67	0.75
Intended Savings, I	0.85	0.85	0.85	0.90	0.43
Domestic Land Market Leakage, L^{DA}	-0.07	0.04	-0.20	-0.17	-0.02
World Land Market Leakage , L^{WA}	0.80	0.89	0.73	0.47	1.25
Domestic Fuel Market Leakage, L^{DF}	-0.49	-0.47	-0.86	-0.49	-0.49
World Fuel Market Leakage, L^{WF}	0.43	0.42	0.50	0.43	0.43

Notes: The low and high cases for the elasticity of crop demand for food production are constructed by doubling and halving the elasticities of substitution in equation (B.2.10). Low agriculture and land use emissions case sets all emissions factors to low values, and lowers the world land use conversion ratios by 20%. High agriculture and land use emissions case sets all emissions factors to high values and increases the world land use conversion ratios by 20%.

Table 2.11: Range of Emissions in 2015

Parameter Case	Central	Best	Worst
Crude Oil Excess Supply Elasticity	Central	High	Low
Fuel and VMT Elasticities of Demand	Central	Low/High	High/Low
Elasticities of Crop Demand for Food Production	Central	High	Low
Agriculture and Land Use Emissions	Central	Low	High
RFS (VEETC Renewed)			
Baseline Ethanol Consumption (billion liters)	45.4	50.0	43.3
Change in Ethanol Consumption	11.4	6.8	13.8
Net Change in Emissions (kgCO_2e per liter ethanol added)	0.40	-0.32	2.01
Intended Savings, I	0.85	0.90	0.42
Domestic Land Market Leakage, L^{DA}	-0.07	-0.23	0.18
World Land Market Leakage , L^{WA}	0.79	0.43	1.37
Domestic Fuel Market Leakage, L^{DF}	0.22	0.05	0.65
World Fuel Market Leakage, L^{WF}	0.31	0.33	0.24
RFS (VEETC Swapped)			
Baseline Ethanol Consumption (billion liters)	45.4	48.0	45.7
Change in Ethanol Consumption	11.1	8.3	11.0
Net Change in Emissions (kgCO_2e per liter ethanol added)	-0.18	-1.36	1.62
Intended Savings, I	0.85	0.90	0.42
Domestic Land Market Leakage, L^{DA}	-0.07	-0.24	0.23
World Land Market Leakage , L^{WA}	0.80	0.41	1.45
Domestic Fuel Market Leakage, L^{DF}	-0.49	-1.21	0.02
World Fuel Market Leakage, L^{WF}	0.43	0.57	0.34

Notes: For the RFS when the VEETC is renewed, the fuel and VMT elasticities of demand are set to the low values in the best case and to the high values in the worst case. When the RFS is swapped for the RFS, the fuel and VMT elasticities of demand are set to the high values in the best case and to the low values in the worst case.



Notes: Change in emissions is relative to the baseline with VEETC. Given that intended emissions savings are roughly equivalent whether or not the VEETC is renewed, only intended emissions savings with the VEETC renewed are displayed in Panel 3.

Figure 2.1: Decomposition of Total Leakage

Chapter 3

On the Trade-Offs of Regulating Multiple Unpriced Externalities with a Single Instrument: Evidence from Biofuel Policies

3.1 Introduction

Despite Tinbergen's (1952) insight that efficient policymaking requires separate policy instruments to correct for separate market failures, policymakers frequently use a single policy instrument to address multiple unpriced externalities. As a consequence, reducing one market failure can exacerbate or alleviate others, implying potentially important trade-offs. The presence of such trade-offs provides a unique opportunity to recover the implicit value that policymakers place on those related unpriced externalities. Such implicit values may not be the same as those inferred from social-cost accounting methods, but they do enhance our understanding of why certain policies are adopted rather than others and why policymakers frequently use a single instrument to address multiple market failures.

A recent example of using a single policy to address multiple unpriced externalities in the US is the Energy Independence and Security Act (EISA) of 2007 which specifies aggressive mandates on the amount of biofuels to be blended into the nation's transportation fuels through 2022. EISA aims to achieve two goals: reduce US dependence on foreign sources of crude oil and reduce greenhouse gas (GHG) emissions from the transportation sector.[1]

In this paper we examine three related issues. First, we evaluate whether the Renewable Fuel Standard (RFS) for conventional biofuels established by EISA passes a simple benefit-cost test under central parameter estimates of external costs. Second, we examine the trade-offs between oil dependency and environmental externalities, which allows us to understand how policymakers balanced these competing objectives under EISA. Finally, we recover policymakers' implicit value of the external costs of oil dependency required for the RFS to pass a benefit-cost test.

To examine these issues we develop an analytical and numerical simulation model. In the spirit of Parry and Small (2005) and much of the earlier literature that examines en-

[1] These two objectives were noted by former President George W. Bush, in signing EISA on December 19th, 2007: "One of the most serious long-term challenges facing our country is dependence on oil—especially oil from foreign lands... Because this dependence harms us economically through high and volatile prices at the gas pump; dependence creates pollution and contributes to greenhouse gas admissions [*sic*]."

vironmental policies in a second-best setting (e.g. Bovenberg and de Mooij (1994), Parry (1995), Bovenberg and Goulder (1996), Goulder et al. (1999), and Bento et al. (2013a)), the framework considers multiple unpriced externalities associated with fuel use and various pre-existing fiscal distortions. The model integrates fuel, food and land markets and links adjustments in these markets to the generation of both environmental and oil dependency related externalities. Final demand in the model reflects the behavior of a representative agent who consumes a numeraire, food and vehicle miles from blended fuel. Blended fuel is produced by combining gasoline with ethanol, where gasoline is produced primarily from crude oil supplied from abroad and ethanol primarily from corn. Domestic crop producers supply corn for ethanol production, corn and other crops for domestic food production and export markets, as well as decide how much land to enroll in a conservation program. Greenhouse gas emissions are calculated across each of these sectors following Bento et al. (2013b).

In addition to contributing to the literature on environmental policy in a second-best setting, our paper contributes to a growing literature that examines the effects of biofuel policies.[2] In particular, our paper is related to the work of Cui et al. (2011), Chen et al. (2012), and EPA (2010). Cui et al. (2011) evaluate several stylized alternative policy regimes including 'first' and 'second-best' optimal policies for corn ethanol for the year 2009 after accounting for externalities from GHG emissions using a simple life-cycle metric. Chen et al. (2012) compute the economic costs and GHG emissions of a biofuel mandate, a low-carbon fuel standard and a carbon tax in 2030 using a model that assumes significant adoption of next generation vehicles and biofuel production pathways.[3] EPA (2010) is the regulatory impact assessment of the expected impacts of the full RFS through 2022 that, in addition to determining whether various biofuel pathways meet the greenhouse emissions reductions required to meet the various biofuel mandates under EISA, also performs a welfare assessment

[2]See de Gorter and Just (2010) for a review. For a broader review of economic and environmental dimensions of biofuels see also Rajagopal and Zilberman (2007).

[3]The biofuel mandate modelled there is similar to the full RFS, although the RFS is only statutorily specified until 2022.

of the entire RFS.

Like these papers, we perform a welfare analysis of the RFS. However, our paper differs from these studies in several important ways. First, we restrict our analysis to the RFS for conventional biofuels through 2015. We do so because there is considerable uncertainty with respect to whether the advanced mandates established by EISA will in fact be achieved. Long run analyses of the RFS that consider both the conventional and advanced mandates require strong assumptions regarding the emergence of second-generation biofuels,[4] whether current technical limits on the amount of ethanol that can be blended into the domestic fuel supply (the so-called 'blend wall') will be amended, whether flex fuel automobiles will achieve large-scale market penetration, and whether sufficient infrastructure will be in place to supply that fleet with high ethanol blends. Cumulatively, such assumptions determine how competitive second generation biofuels will be relative to corn ethanol, and thus the amount of various biofuel classes that will be added by the RFS in the long run. More importantly, this can imply substantially different price adjustments in fuel and land markets, which will impact a welfare analysis of the RFS for conventional biofuels. By focusing on the RFS for conventional biofuels through 2015, we have more confidence in our ability to isolate the welfare impacts of just the RFS for conventional biofuels since mandated volumes for second generation biofuels are likely to be negligible in this time horizon, and our estimates are not affected by these assumptions.

Second, recognizing that there is considerable uncertainty surrounding estimates of key external benefit parameters, we conduct a Monte Carlo analysis over these parameters and calculate the frequency at which the policy passes the benefit-cost test.

Third, we use our welfare framework to examine the trade-offs between oil dependency and environmental externalities that emerge as a result of using a single instrument to address both channels of externalities. While many second-best analyses examine the impacts

[4]For instance, there remains considerable uncertainty regarding farmers' willingness to plant second-generation feedstocks, the yields of second generation feedstocks, and the true marginal costs of producing second generation biofuels.

of policies in the presence of multiple pre-existing externalities and distortions, we exploit uncertainty in external cost parameters to infer how policymaker's trade-off competing objectives of the RFS. In addition, we recover the value that policymakers would have to place on oil dependency related externalities in order for the RFS for conventional biofuels to pass a benefit-cost test. This is related in spirit to the work on bureaucratic decision-making (McFadden (1975), Cropper et al. (1992), Timmins (2002)), which aims to infer from observed policy choices policymakers revealed preferences. While this earlier work relies upon repeated policy choices in an econometric setting, our paper demonstrates how large-scale simulation models that comprehensively account for uncertainty across important welfare dimensions can be used to the same end.

We highlight the following key findings. First, the RFS consistently fails a benefit-cost test with net costs totalling \$1.6 billion or \$0.79 per energy content adjusted gallon of ethanol added by the RFS in 2015. Second, we find that each dollar reduction in the external costs of oil dependency achieved by the RFS comes at the expense of additional environmental external costs of \$0.90 in 2015, suggesting that policymakers trade-off the environmental objectives of the RFS with the oil dependency objectives almost dollar for dollar. Third, policymakers would have to value the external costs of oil dependency at \$1.11 per gallon of gasoline in order for the RFS to pass a benefit-cost test, which is more than five times our central literature estimate of the oil premium. Finally, if policymakers intended to replace the pre-existing ethanol subisidy—which was in place when EISA was established, but was recently allowed to expire—with the RFS, then the RFS would pass a benefit-cost test a quarter of the time, there would be a net external environmental benefit of \$1.28 for every dollar reduction in the external costs of oil dependency, and policymakers implicit value of oil dependency would instead be \$0.36 per gallon of gasoline. These results suggest that the decision to address multiple externalities with a single policy has more to with getting policymakers with divergent preferences on board then with maximizing efficiency.

The rest of the paper is organized as follows. Section 3.2 provides additional details on the policies considered in this paper. In Section 3.3 we present our analytical model and decompose the welfare effects of the RFS for conventional biofuels in the presence of multiple externalities and pre-existing distortions. We also derive an expression for policymaker's implied value of oil dependency. Section 3.4 discusses our simulation model which closely follows our analytical model and presents the results of our numerical analysis. Finally, Section 3.5, concludes.

3.2 Policy Details

Historically, biofuels in the US have been supported by a variety of policies at both the state and federal levels. Here we discuss the two federal polices that are most relevant for the analysis: the Renewable Fuel Standard (RFS) for conventional biofuels, and the Volumetric Ethanol Excise Tax Credit. Details regarding other policies that impact ethanol production in the US are provided in the Appendix.

3.2.1 Renewable Fuel Standard (RFS)

The RFS was established by the Energy Independence and Security Act of 2007 (EISA) with rule-making authority given to the US EPA (US Congress, 2007). The RFS is a set of nested mandates specifying the minimum amount of various classes of biofuels that must be blended into the nation's fuel supply, where biofuels are classified according to the life-cycle GHG emissions savings they achieve relative to a fossil fuel derived alternative (gasoline or diesel). The national RFS targets all biofuels that achieve a reduction of at least 20%.[5] Below the national RFS, the RFS for advanced biofuels targets all biofuels that achieve a savings of at least 50%. Since conventional biofuels such as corn ethanol do not meet this threshold, we define the *RFS for conventional biofuels* as the national RFS less the RFS for advanced biofuels. Within the RFS for advanced biofuels, there are separate standards for "cellulosic biofuel", which targets cellulosically derived biofuels that must achieve emissions savings of

[5]Specifically, only biofuels from new facilities that commenced construction after December 19, 2007 must meet this standard. Production from facilities built prior are grandfathered in under EISA 2007.

60% or more, and "biomass-based diesel" which targets biodiesel that must achieve savings of 50% more.

The RFS for conventional biofuels expands from 4 billion gallons in 2006 to 15 billion gallons in 2015, after which it remains constant through 2022. The (EPA, 2010) has determined that domestically produced corn ethanol just meets this requirement, achieving life-cycle savings of 21%. It is widely expected that this mandate will be predominantly filled by corn ethanol, given that it is the most cost competitive biofuel in widespread production in the US.

There are legitimate reasons to question whether the volumes originally set for advanced biofuels will be achieved in the short run, including the EPA's statutory authority and past willingness to scale down the cellulosic ethanol mandate, current technical limits on the amount of ethanol that can be blended into fuel (the so-called "blend wall"), and constraints on the expansion of ethanol imports.[6] Given this, as well as the lack of credible data on feedstock production and technological conversion efficiency for advanced biofuels, we do not consider the RFS for advanced biofuels in our analysis. A complete discussion regarding our decision to abstract from the RFS for advanced biofuels is provided in the Appendix.

3.2.2 Volumetric Ethanol Excise Tax Credit

The VEETC is an excise tax credit (deducted from the federal fuel tax) of $0.45 per gallon provided to the fuel blender for each unit of ethanol they add into the fuel supply. The VEETC expired at the end of 2011, nearly half a decade after the current RFS was established by EISA. Prior to its expiration, ethanol production had been subsidized since the 1978 Energy Tax Act. The VEETC was by far the most significant federal support program for biofuels until the RFS was established. Under a non-binding RFS, the VEETC acted as an implicit agricultural support program; however under a binding RFS, the VEETC provides

[6]EISA 2007 includes a "cellulosic loophole" which effectively allows the EPA to scale down the RFS for cellulosic biofuels if production capacity to meet the mandated quantities does not exist. Using this authority, the EPA has lowered the required volumes of cellulosic biofuels to less than 7% of the level set by EISA 2007 in 2010, 2011 and 2012.

no additional support.[7] Since one of our objectives is to understand policymakers' revealed preference for externalities, it is especially important that we account for the VEETC. The VEETC was in place prior to EISA's passage in 2007 and likely would have remained in place had EISA not established binding biofuel mandates. Once policymakers established a binding RFS, however, it is not clear whether they also intended to retain the VEETC in perpetuity. As such, we assess the welfare implications of the RFS both when the VEETC is assumed to remain in place alongside the RFS as well as when the RFS replaces the VEETC entirely.

3.2.3 Additional Pre-existing Policies Likely to Interact with the RFSm

In addition to the VEETC, the RFS interacts with several other pre-existing policies in the economy. First, federal and state governments tax blended fuel at an average rate of \$0.47 per gallon. Second, the USDA administers the Conservation Reserve Program (CRP), a land set-aside program that allows farmers to voluntarily take historical cropland out of agricultural production in exchange for an annual rental payment.[8]

[7] Although the expiration of the VEETC was initially opposed by feedstock and ethanol producer groups, many of these groups eventually acquiesced, largely, it appears, due to the presence of the RFS. According to Matthew A. Hartwig of the Renewable Fuels Association: "We may be the only industry in U.S. history that voluntarily let a subsidy expire... The tax incentive is less necessary now than it was just two years ago... We don't expect the price of corn to fall or rise just because the tax incentive goes away. We will produce the same amount of ethanol in 2012 as in 2011, or more"(Pear, 2012). Given the adeptness of these same groups to retain subsidies for ethanol in some form or other for over thirty years, it is likely that the VEETC would have been retained were the RFS not in place.

[8] In actuality, there are four major CRP programs with varying contract lengths, payment rates and enrollment qualifications. Two of these programs, the Conservation Reserve Enhancement Program (CREP) and the Farmable Wetland Program (FWP) target specific environmental objectives and offer higher rental rates making this land unlikely to be converted to cropland. We therefore assume that only land in the remaining two major programs, general sign-up and continuous non-CREP, will be available for conversion to cropland. Thus when we refer to 'CRP' land, we are referring only the sum of these two sub-categories. Of these two categories, general sign-up provides the bulk of our measure of CRP, constituting on average 92% of our CRP measure between 2003 and 2010. Loan Deficiency Programs, Marketing Assistance Loans, and Counter-cyclical and Direct payments also provide small subsidies to agricultural producers in the US. Accounting for these programs in our analysis has a negligible impact on our welfare results and so we omit them for simplicity. In addition, there is a very small tariff on crude oil imports of \$0.053 (API gravity of 25 degrees or less) to \$0.105 (API gravity of 25 degrees or more) per barrel of crude oil for imports to the US from countries other than Canada that is not included in our analysis here. This amounts to \$0.003 to \$0.006 per gallon of gasoline produced from a barrel of imported crude oil, which is also negligible and so not incorporated into our analysis here.

3.3 Analytical Model

In this section we develop an analytical model, which shares many of the features of earlier work by Parry and Small (2005), and which we use to decompose the welfare effects of the RFS for conventional biofuels.

3.3.1 Model Assumptions

General Environment

We consider a static model of two countries, D and W, both open economies. D denotes the United States; W represents the rest of the world, which we take to denote a collection of small open economies that trade with the US. Countries trade agricultural crops and crude oil.[9] We model explicitly the behavior of the agents in the US economy, and treat trade with the rest of the world in a more simplified fashion.[10]

Consumer Demand

We consider a representative household that receives utility from vehicle-miles traveled, M, food, X, a numeraire good, C, and the stream of environmental services provided by land allocated to the Conservation Reserve Program (CRP), K. In addition, the household experiences dis-utility from time spent driving, T, global and local air pollutants, D, severity-adjusted traffic accidents, Z, and oil dependency, J. The household's utility function is given by:

$$U = u\left(M, C, X\right) + \xi(K) - \nu(T) - \psi(D) - \kappa(J) - \mu(Z). \tag{3.3.1}$$

[9] We abstract from the trade of gasoline. Between 2005 and 2009, the US imported less than 3% of total finished gasoline consumed, and exported less than 5% of total gasoline produced according to the US Energy Information Administration.

[10] In what follows, we omit the subscript D as appropriate for ease of notation. Upper-case letters signify quantities. Lower-case letters denote prices; prices denoted by the letter w are functions of final prices, which are denoted by the letter p and which are identified in equilibrium. All variables are expressed in per capita terms.

Vehicle miles travelled are produced according to:

$$M = M\left(F, L^H\right), \tag{3.3.2}$$

where F is total blended fuel consumption and L^H is a monetary measure of other driving costs that depend on vehicle price and attributes. $M(\cdot)$ permits a nonproportional relationship between blended fuel consumption and vehicle miles travelled. If the RFS causes the price of blended fuel to fall, for example, the representative household may drive more (increase M) and invest in less fuel economy (substitute from L^H to F).

The representative agent has fixed endowments of labor, $\bar{L}$, and land, $\bar{A}$ and maximizes (3.3.1) subject to income and time constraints, given respectively, by:

$$\begin{aligned} C + w^X X + w^F F + L^H &= \left[\left(1 - t^L\right) L + \pi^A + G + B\right], \\ L + T &= \bar{L}, \end{aligned} \tag{3.3.3}$$

where w^X is the price of food, w^F is the price per gallon of blended fuel, t^L is a tax on labor income, π^A is the net returns to the agent's land endowment, G is a lump-sum transfer from the government, and B is the net trade balance. Unlike Parry and Small (2005), we abstract from the distortions caused by the labor tax and so do not model the labor/leisure choice. We normalize all prices in the economy to the wage rate, which is set equal to one. Driving time is given by:

$$T = \tau\left(\bar{M}\right) M, \tag{3.3.4}$$

where τ is the inverse of average travel speed with $\tau' > 0$ and $\bar{M}$ is aggregate miles driven per capita. The representative household does not take account of their own impact on congestion, e.g. they take $\tau\left(\bar{M}\right)$ as fixed.

The household chooses M, F, L^H, X, and C to maximize utility (3.3.1) subject to (3.3.2) and (3.3.3). The resulting uncompensated demand functions for vehicle miles travelled, blended fuel, fixed costs of driving, food, and the numeraire are given by:

$$
\begin{gathered}
M\left(w^F, w^X, t^L, G, \pi^A\right) \qquad X\left(w^F, w^X, t^L, G, \pi^A\right) \qquad C\left(w^F, w^X, t^L, G, \pi^A\right) \\
F\left(w^F, w^X, t^L, G, \pi^A\right) \qquad L^H\left(w^F, w^X, t^L, G, \pi^A\right).
\end{gathered} \tag{3.3.5}
$$

Fuel Markets

Blended fuel is produced from gasoline (P) and ethanol (E) with a constant returns to scale production function given by:[11]

$$F = F(P, E). \tag{3.3.6}$$

The RFS is modeled as a share mandate for ethanol in the production of blended fuel:[12]

$$E \geq \theta F \tag{3.3.7}$$

where θ is the mandated share of ethanol per unit of blended fuel, such that the RFS mandated quantities are achieved.[13]

[11] Here we present a general formulation for the production of blended fuel. In the simulation model below, we assume that gasoline and ethanol are energy equivalent perfect substitutes. This appears to be the most common specification used in the literature (see de Gorter and Just (2009)), although not the only one (see Vedenov and Wetzstein (2008) and Ando et al. (2010)). We believe this is an appropriate representation because consumers, when they purchase blended fuel, are largely unaware of the share of ethanol in the fuel they are purchasing. Consumers are, however, sensitive to the fuel economy of the blended fuel they purchase with respect to various retailers, which sell different fuel blends.

[12] We note that EISA established a trading program to ease compliance with the RFS, whereby each unit of biofuel produced is assigned a unique Renewable Identification Number (RIN). These RINs can be separated from the biofuel sold, and can thus be traded independently of the biofuel itself. Individual blenders are required to have enough RINs and/or RIN enumerated ethanol blended into their annual production, so that they meet their individual portion of the RFS (their Renewable Volume Obligation). Since we model a nationally representative fuel blender in order to evaluate a federal policy, spatial smoothing using RINs is not an issue. In effect, this assumes that the market for RINs is efficient and that the RIN market closes in each year.

[13] While the RFS itself states the total amount of ethanol that must be used, in practice the EPA annually determines the minimum share of ethanol that must be mixed into each liter of blended fuel. The blend requirement is set such that, given projected demand for blended fuel, the resulting total consumption of ethanol in a given year approximately equals the RFS (US EPA, 2010). A related concern, affects the extent to which ethanol as an input in blended fuel is restricted due to technical limitations that are largely under the regulatory purview of the EPA. This so-called 'blend-wall' currently restricts the amount of ethanol that

The fuel blender chooses E and P to minimize:

$$w^P P + \left(w^E - s^E\right) E + t^F F, \tag{3.3.8}$$

subject to equation (3.3.6) and (3.3.7), where w^E and w^P, are the prices of ethanol and gasoline, respectively, s^E is the VEETC, and t^F is the fuel tax. The resulting price of blended fuel, is given by:

$$w^F \left(w^P, w^E - s^E, \theta, t^F\right), \tag{3.3.9}$$

and the demand functions for gasoline and ethanol are:

$$P = p_F \left(w^P, w^E - s^E, \theta, t^F\right) F(\cdot) \qquad E = e_F \left(w^P, w^E - s^E, \theta, t^F\right) F(\cdot) \tag{3.3.10}$$

where $p_F(\cdot)$ and $e_F(\cdot)$, are the per-unit conditional factor demands for gasoline and ethanol, and $F(\cdot)$ is the uncompensated demand for blended fuel given in (3.3.5).

Gasoline and ethanol are produced by perfectly competitive firms with constant returns to scale production technology; gasoline is produced from crude oil, R^P, and labor, L^P, and ethanol is produced from corn, Y^E, and labor, L^E.[14] The production functions for gasoline and ethanol are given by:

$$P = P\left(R^P, L^P\right) \qquad E = E\left(Y^E, L^E\right). \tag{3.3.11}$$

The prices of gasoline and ethanol can be written as functions of the price of crude oil, $w^P\left(p^R\right)$, and the price of corn, $w^E\left(p^Y\right)$, respectively. Finally the factor demand functions

can be mixed into blended fuel to be 10% or less. Since we analyze the RFS for conventional biofuels through 2015, we remain under this blend wall and so this is not a concern for our analysis.

[14]Here Y^E is net of co-products, which can be used in livestock rations. In the simulation model, co-products are produced jointly with ethanol and substitute for corn and soybeans in the production of food. See the Appendix, section C.3 for additional details.

are given by:

$$Y^E\left(p^Y, E(\cdot)\right) \qquad L^E\left(p^Y, E(\cdot)\right) \qquad R^P\left(p^R, P(\cdot)\right) \qquad L^P\left(p^R, P(\cdot)\right) \tag{3.3.12}$$

where $E(\cdot)$ and $P(\cdot)$ are from (3.3.10).

Land-Use Allocation

The representative household maximizes the net returns to its land endowment by allocating land to the production of crops, or setting land aside in CRP. Cropland can be allocated to corn production, Y, which can be used to produce food or ethanol, and other crops, Z which are used exclusively for food production.[15] Letting i index the three uses, $\{Y, Z, N\}$, the allocation of the land endowment is determined by:

$$\pi^A\left(p^Y, p^Z, \bar{A}\right) = \max_{A_i} \sum_{i\in\{Y,Z\}} \left(p^i y_i\left(A_i\right) - l_i\right) A_i + s^N\left(A_N\right) A_N$$

subject to:

$$\sum_i A_i \leq \bar{A} \tag{3.3.13}$$

where p^Y and p^Z are world prices for corn and other crops, respectively, A_i is the quantity of land allocated to land use i and l_i is the amount of labor required per unit of land used to produce crop i. The functions $y_Y\left(A_Y\right)$ and $y_Z\left(A_Z\right)$ represent the yields of corn and other

[15] In our simulation model, we disaggregate Z further and consider soybeans, hay, wheat and cotton. Every year since 1980, these five crops have made up at least 80% of total principal crops (corn, sorghum, oats, barley, wheat, rice, rye, soybeans, flaxseed, peanuts, popcorn, cotton, hay, dry beans, dry peas, potatoes, sweet potatoes, tobacco, sugarcane and sugarbeets) harvested. In 2003, these five crops accounted for 91% of principal crops harvested and 82.7% of the total value of field crop production. We abstract from other domestic land uses, such as pastureland, forest and rangeland. According to the 2007 Natural Resources Inventory, between 2002 and 2007 conversion of rangeland and forest accounted for only 0.2% of cropland in 2007, and conversion of pastureland only 0.8% of cropland in 2007 U.S Department of Agriculture (2009). This reflects the fact that much of what constitutes rangeland, forest, and pastureland is of considerably lower quality than cropland and/or has a high cost of conversion. However, we do include land used to produce continuous hay, the cultivable component of pastureland most likely to be brought into agricultural production.

crops respectively. The function $s^N(A_N)$ represents the per unit land CRP rental payment. Both $y_i(A_i)\ \forall\, i \in \{Y, Z\}$ and $s^N(A_N)$ are assumed to be monotonically decreasing and concave to reflect decreasing returns to expanded agricultural production and decreasing rental payments for land held in CRP.[16]

The first-order conditions of (3.3.13) provide the crop supply functions, as well as the optimal allocation of land to set-aside in the CRP:

$$\begin{aligned} Y\left(p^Y, p^Z, \bar{A}\right) &= y_Y\left(A_Y\left(p^Y, p^Z, \bar{A}\right)\right) A_Y\left(p^Y, p^Z, \bar{A}\right), \\ Z\left(p^Y, p^Z, \bar{A}\right) &= y_Z\left(A_Z\left(p^Y, p^Z, \bar{A}\right)\right) A_Z\left(p^Y, p^Z, \bar{A}\right), \\ A_N\left(p^Y, p^Z, \bar{A}\right). & \end{aligned} \tag{3.3.14}$$

Food Production

Food is produced from corn and other crops by competitive firms with constant returns to scale technology:[17]

$$X = X\left(Y^X, Z^X, L^X\right) \tag{3.3.15}$$

where Y^X, Z^X and L^X are the quantities of corn, other crops and labor used in food production respectively. Incorporating food production in the model allows us to explicitly capture the trade-off between demand for crops for food production, and demand for crops for ethanol production. The food producer chooses Y^X, Z^X, and L^X to minimize costs subject to (3.3.15). Given the uncompensated demand for food from (3.3.5), the conditional factor demands for corn, other crops, and labor are given by:

$$Y^X\left(p^Y, p^Z, X(\cdot)\right) \qquad Z^X\left(p^Y, p^Z, X(\cdot)\right) \qquad L^X\left(p^Y, p^Z, X(\cdot)\right), \tag{3.3.16}$$

[16] Decreasing returns reflects that land is of heterogeneous quality and thus exhibits declining marginal soil productivity from specialization (Howitt, 1995).

[17] We treat food as a composite of all final food products. As such our food sector encompasses intermediate sectors such as livestock production.

and $w^X(p^Y, p^Z)$ is the price of food.

Crop Export Demand

The rest of the world responds to the RFS only through price channels. We consider a simplified model of crop exports with the rest of world excess demand for crop exports given by:

$$Y^{X,W} = Y^{X,W}\left(p^Y, p^Z\right) \qquad Z^{X,W} = Z^{X,W}\left(p^Y, p^Z\right). \tag{3.3.17}$$

Crude Oil Supply

The net supply curve for crude oil is given by:[18]

$$R^W = R^W\left(p^R\right), \tag{3.3.18}$$

where R^W is the net amount of crude oil supplied to the US.[19]

Government

The government raises revenue by imposing taxes on blended fuel, t^F, and labor, t^L, and finances three programs: a per acre rental payment to land that is set aside in the CRP, s^N, the VEETC, s^E, and a lump-sum transfer to the representative household, G, which is allowed to adjust such that the government's budget balances according to:

$$t^F F + t^L L = G + s^N A_N + s^E E. \tag{3.3.19}$$

[18]Net supply of crude oil equals the sum of crude oil supplied by the rest of the world plus US supply of crude oil less the amount of crude oil demanded in the US for non-gasoline uses. See Appendix for additional details. Consistent with our calculation of the oil premium, we do not consider oligopoly power in the rest of world supply of crude oil.

[19]Given the simplified nature in which we treat trade with the rest of the world, the net trade balance must be accounted for in order for the model to close. This is the term B in (3.3.3). Formally, this is: $B = \hat{Y}^{X,W}p^Y + \hat{Z}^{X,W}p^Z - \hat{R}^W p^R$, where hat here denotes import/export volume.

Characterization of the Economic Equilibrium

An economic equilibrium consists of a price vector, $\left[p^Y, p^Z, p^R, G\right]$, such that the world markets for agricultural crops and crude oil and the labor market in the US all clear.

Categories of External Costs

Air Pollution

We consider damages arising from two classes of air pollutants: greenhouse gases (GHG) and local air pollutants. Local air pollutants depend on aggregate miles driven, $\bar{M}$, whereas GHG emissions depend on total blended fuel consumption, $\bar{F}$, and the share of ethanol in blended fuel, $\frac{\bar{E}}{\bar{F}}$.[20] Thus total damages from air pollutants is given by:

$$D = D_M(\bar{M}) + D_{GHG}\left(\bar{F}, \frac{\bar{E}}{\bar{F}}\right), \tag{3.3.20}$$

where $D_{GHG}(\cdot)$ is the damages from GHG emissions, $D_M(\cdot)$ is the damages from local pollutants. We assume that $D'_{GHG} > 0$ and $D'_M > 0$.

Oil Dependency

We refer to the marginal external costs of oil dependency, expressed in dollars per gallon of gasoline consumed in the US as the *oil premium*. Prior literature has emphasized two main channels of external costs from oil dependency: a *monopsony* component owing to the fact that since the US is a sufficiently large purchaser of foreign oil supplies it can impact the

[20] Our treatment of local air pollution follows Parry and Small (2005). We abstract from how local air pollution may be impacted by fuel composition, which is a minor concern given that we are only considering low-level ethanol blends of 10% ethanol or less. GHG emissions in Parry and Small (2005) are generated solely through the aggregate consumption of blended fuel, $\bar{F}$. However, given that estimates of the life-cycle emissions of biofuels have emphasized equilibrium price adjustments (Searchinger et al. (2008), EPA (2010), Bento et al. (2013b)), such an approach would be unsatisfactory here. We capture this here by allowing GHG emissions to vary both upon aggregate fuel consumption as well as fuel composition as reflected by $\frac{\bar{E}}{\bar{F}}$. This reflects changes in emissions throughout the economy including those related to adjustments in national and international land and fuel markets. In the simulation model, we calculate the equilibrium change in emissions using the approach developed in Bento et al. (2013b), which attaches emissions coefficients to the sectors of the economy that adjust in response to the RFS. We refer the reader to the Appendix, section C.6 for further details.

world price of crude oil, and a *volatility* component resulting from economic disruption costs that are incurred as a result of unanticipated economic shocks affecting the world crude oil market. Here, we also consider a third channel of external costs, *national security*, which reflects the costs of securing the nation's crude oil supplies.[21] We include this component for two reasons. First, the RFS is a large-scale policy intended to achieve non-marginal changes in the nation's consumption of crude oil. Second, EISA was established to explicitly address this aspect of oil dependency. We consider damages arising from oil dependency in the crude oil and gasoline markets on a per gallon basis of the aggregate amount of gasoline, $\bar{P}$, consumed in the US. This is given by:

$$J = j(\bar{P})\bar{P}, \tag{3.3.21}$$

where $j(\bar{P})$ is the average marginal external damages from oil dependency.

Accidents

External costs arising from accidents depend on aggregate miles driven and is given by:[22]

$$Z = z(\bar{M})\bar{M}, \tag{3.3.22}$$

where $z(\bar{M})$ is the average per mile external damages from accidents.

[21] Some authors also include the costs of OPEC oligopoly power as an additional oil dependency market failure (Kaufmann et al., 2004; Greene and Ahmad, 2005). While OPEC has operated as an imperfect cartel in the past Griffin and Xiong (1997), evidence from more recent periods suggests this is less of a concern Bremond et al. (2012). As such, we do not consider this component in our calculation of the oil premium. *National security* includes military and diplomatic expenditures from recurring troop and military asset deployment to strategic oil producing regions, one-off costs for wars, as well as the operational costs of running and establishing the Strategic Petroleum Reserve (SPR). Some analysts do not include this component in the oil premium; see Leiby et al. (1997); Parry and Darmstadter (2003); Greene and Ahmad (2005); Leiby (2007). For additional discussion of the three components we do consider, including details and assumptions underlying how these terms are calculated, see the Appendix, section C.8.

[22] Some accident costs are internalized by the consumer, for example, by purchasing insurance. These costs are included in L^H. However, other costs are not considered by individuals when deciding how much to drive, such as: costs arising from delays in travel, injuries and fatalities to pedestrians, and a portion of property damages.

Environmental Benefits of CRP

Finally, the external benefits provided by holding land in CRP is given by:[23]

$$K = k(\bar{A}_N)\bar{A}_N, \tag{3.3.23}$$

where $k(\bar{A}_N)$ is the average per acre external benefit provided by placing land in CRP, and $\bar{A}_N$ is the total amount of land held in CRP.[24]

3.3.2 The Welfare Effects of the RFS

Consider a marginal increase in the RFS. The change in welfare due to this increase is given by (see Appendix, section C.1 for full derivation):

$$\begin{aligned}
-\frac{1}{\lambda}\frac{dV}{d\theta} = {} & \underbrace{w^F\frac{dF}{d\theta}}_{dW^{\mathrm{PC}}} + \underbrace{s^E\frac{dE}{d\theta}}_{dW^{\mathrm{E}}} + \underbrace{\left(MEC^F - t^F\right)\frac{dF}{d\theta}}_{dW^{\mathrm{F}}} \\
& + \underbrace{MEC^P\frac{dP}{d\theta}}_{dW^{\mathrm{P}}} + \underbrace{\left(MEB^N - s^N\right)\left(-\frac{dA_N}{d\theta}\right)}_{dW^{\mathrm{N}}} \\
& + \underbrace{Y^{X,W}\frac{dp^Y}{d\theta} + Z^{X,W}\frac{dp^Z}{d\theta} - R^W\frac{dp^R}{d\theta}}_{dW^{\mathrm{B}}},
\end{aligned} \tag{3.3.24}$$

where, λ is the marginal utility of income.

dW^{PC} is the *primary cost* of the RFS. This term equals the price of blended fuel multiplied by the change in blended fuel induced by the RFS, and varies in proportion to the amount of ethanol added by the RFS.[25]

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[23]These include the benefits from wildlife viewing, hunting, water quality, soil quality improvements, and air quality improvements (excluding GHG emissions).

[24]We note that the signs on j', z', and k' are ambiguous. For example, with respect to z', if greater consumption of vehicle miles travelled increases traffic density, accidents will become more frequent but less severe as people drive more closely at slower speeds.

[25]Since the RFS affects the input markets for blended fuel (ethanol and gasoline), the primary cost can be measured as the sum of the distortions generated in each input market, or alternately as the distortion generated in the output market for blended fuel which is what is presented here.

dW^{E} is the *subsidy interaction effect* and equals the VEETC multiplied by the change in ethanol induced by the RFS.

dW^{F} is the *blended fuel output effect*. It is the wedge between the marginal external cost of blended fuel consumption (MEC^F) and the fuel tax multiplied by the change in blended fuel induced by the RFS. MEC^F includes the marginal external costs of VMTm related externalities (local air pollution or MEC^M_{LP}, accidents or MEC^M_A, and congestion or MEC^M_C) as well as the external costs of GHG emissions (MEC^{GHG}). Whether dW^{F} is positive or negative depends on the impact of the RFS on the price of blended fuel as this determines whether MEC^F is positive or negative.[26] This implies a welfare gain (loss) if the RFS causes the price of blended fuel to increase (decrease).

dW^{P} is the *oil premium effect*. This equals the oil premium multiplied by the change in gasoline induced by the RFS. Since the RFS induces fuel blenders to alter their input mix towards ethanol, the amount of gasoline demanded by blenders as a result of the RFS will always fall. However, if the RFS causes the price of blended fuel to rise (fall), then the magnitude of this decline will be greater (smaller) as the amount of blended fuel consumed falls (increases), implying an output effect by fuel blenders that reinforces (offsets) the fall in gasoline induced by input substitution.

dW^{N} is the *CRP interaction effect*. This equals the wedge between the marginal external environmental benefit provided from placing an acre of land in CRP and the average rental payment paid to landowners, multiplied by the reduction in land held in CRP as a result of the RFS.

Finally, dW^{B} is the *change in the trade balance*. This term reflects a transfer from the rest of the world to the US. Since the RFS drives up world crop prices, US crop exporters will post greater export receipts. In addition, since the RFS displaces crude oil in the rest

[26]Note that in our numerical simulations, that $\left|MEC^F\right| \geq t^F$ since the sum of the marginal external costs of VMTm related externalities are large relative to t^F. This is consistent with Parry and Small (2005). In our case, the external costs from GHG emissions can also be positive or negative depending upon whether the RFS causes an increase or decrease in emissions. Following Bento et al. (2013b), upon which our emissions calculations are based, whether this occurs also depends upon the change in the price of blended fuel induced by the RFS with emissions increasing (decreasing) when the price of blended fuel decreases (increases).

of the world and thus lowers the world price of crude oil, US crude oil importers will remit fewer import payments to crude oil exporters abroad. Consequently, this term will imply an unequivocal welfare gain as the net trade balance shifts in favor of the US as a result of the RFS.

Policymakers Implicit Value of the External Costs of Oil Dependency

The welfare formula in (3.3.24) can be further manipulated to reveal the lower bound on the implicit value that policymakers place on the external costs of oil dependency, $I\left[MEC^{P}\right]$. This is the value of MEC^{P} for which the RFS just passes a benefit-cost test and is solved for by setting (3.3.24) to zero and isolating $I\left[MEC^{P}\right]$ on the left-hand side:[27]

$$\begin{aligned} I\left[MEC^{P}\right] = \left(-\frac{d\theta}{dP}\right)\Big(& dW^{*} + dW^{\mathrm{N}}\left(MEB^{N}\right) \\ & + dW^{\mathrm{F}}\left(MEC^{GHG}, MEC^{M}_{LP}, MEC^{M}_{A}, MEC^{M}_{C}\right)\Big), \end{aligned} \tag{3.3.25}$$

where $dW^{*} = dW^{\mathrm{PC}} + dW^{\mathrm{E}} + dW^{\mathrm{B}}$ is the sum of all the welfare components that do not depend upon the external cost parameters, MEC^{GHG}, MEC^{M}_{LP}, MEC^{M}_{A}, MEC^{M}_{C}, and MEB^{N} are the marginal external benefits to holding land in CRP.[28] Similar to (3.3.25), we can evaluate the trade-offs between the oil dependency and environmental objectives of the RFS. Our measure of these trade-offs is the change in net environmental external benefits, which is the sum of all the external environmental benefit terms reported in equation (3.3.24), over the *oil premium effect*.[29]

[27]Since we identify $I\left[MEC^{P}\right]$ based on equality here, our measure of the implicit value that policymakers place on the external costs of oil dependency should be considered a lower or conservative bound, e.g. policymakers must have viewed the benefits from the RFS as exceeding or being just equal to the costs of the program.

[28]These expressions as well as MEC^{P} emerge from the analytical model provided above given (3.3.1), (3.3.4), (3.3.20), (3.3.21), (3.3.22), (3.3.23). See Appendix section C.1 for additional details.

[29]In the numerical model $I\left[MEC^{P}\right]$ is identified over 2,000 random draws of the vector of external costs parameters (excluding the oil premium), $\left[MEC^{GHG}, MEC^{M}_{LP}, MEC^{M}_{A}, MEC^{M}_{C}, MEB^{N}\right]$. To evaluate trade-offs, we exploit 2,000 random draws of the vector of external costs parameters that also includes MEC^{P}.

3.4 Numerical Results

We supplement the analytical model developed above with a numerical model which we use to quantify each of the terms in equation (3.3.24) for the years 2009-2015. We compute GHG emissions by linking this model with a sectorally disaggregated emissions model following Bento et al. (2013b).

We assess the welfare effects of the RFS relative to a baseline where the VEETC remains in place through 2015. This implicitly assumes that, in the absence of the RFS, policymakers would have otherwise continued to support biofuels through the VEETC which is fully consistent with the US's long history of biofuel support through subsidization. This baseline is essential for examining the welfare impacts of the RFS from the perspective of policymakers at the time when EISA was passed since the VEETC was in place at that time.

Relative to this baseline, we consider two policy regimes. Our first policy regime imposes the RFS, while retaining the VEETC already in place through 2015. This isolates just the RFS relative to a pre-existing policy regime that includes the VEETC. With the RFS in place, however, it is less clear whether policymakers intended to keep both the RFS and VEETC in perpetuity, and in fact the VEETC was allowed to expire at the end of 2011. Therefore, we also consider a second policy regime in which the RFS is imposed but the VEETC is removed for all years through 2015. This simulation isolates the effects of swapping the VEETC with the RFS.

We complement our central welfare results with a Monte Carlo analysis. Treating the central, lower and upper literature estimates of our external cost parameters as the realizations of the 50^{th}, 10^{th} and 90^{th} percentiles, we fit a separate gamma probability distribution function for each component of external costs. We then randomly draw 2,000 vectors of external cost parameters to perform our Monte Carlo analysis.

We refer the reader to the Appendix for a full discussion of the functional forms used in the numerical model, the data sources used to calibrate the model parameters, the assumptions regarding how model parameters evolve over time, and a discussion of the central, upper and lower parameter values used in the Monte Carlo analysis. Table C.1 presents several of the key elasticities and emissions factors used in the numerical model. These are consistent with literature values. Complete results for the first regime are provided below followed by the results of our Monte Carlo analysis for both the first the second regimes. All other results for the second regime are provided in the Appendix.[30]

Model Validation

We validate the baseline predicted by our model by running our model for each year between 2004 and 2009 and comparing the resulting predictions to observed data for these years. Over this period either the RFS was not in place (pre-2006) or resulted in ethanol volumes significantly above mandated levels (post-2006), and thus was not binding. The full results of this analysis are presented in Table C.9 in the Appendix. In general, our model performs quite well especially in light of the highly variable crop and crude oil prices over this period. On average between 2004 and 2009, we slightly under predict observed harvested acreage for corn, soybeans, and CRP acreage by 1.8%, 0.6%, and 1.5%, respectively, while over-predicting wheat by 1.1%. We over-predict ethanol in our baseline by 8.6% on average.[31]

3.4.1 Impacts on Ethanol Production

Table 3.1 presents the impact of the RFS for conventional biofuels on the amount of corn ethanol consumed in the economy. In the absence of the RFS, ethanol expands gradually year over year from 11.3 billion gallons in 2011 to 12.0 billion gallons in 2015. If the VEETC were not present in the baseline ethanol would instead increase from 5.4 billion gallons in 2011 to 8.2 billion gallons in 2015. Thus, the VEETC was critical for making ethanol cost

[30]While these two regimes aim to capture recent changes in biofuel policy, we report results for all years through 2015. Thus, the second policy regime compares a baseline with the VEETC to a counterfactual of just the RFS for all years, not just from 2012 onward following the expiration of the VEETC at the end of 2011.

[31]Prior to 2009, observed ethanol volumes easily exceeded the mandates in place at this time. This is widely attributed to the growth in gasoline prices over this period as well as the presence of the VEETC. Since we slightly over-predict, this holds true in our model as well.

competitive with gasoline. Thus, the presence of the VEETC in the baseline means that the RFS adds ethanol to a market that is already substantially elevated as a result of the VEETC. For each year from 2010 onwards, the RFS requires that more ethanol be blended into the nation's fuel supply than that predicted in our baseline. In 2011 the RFS drives up the amount of ethanol consumed by 1.3 billion gallons or an increase of 11.3% relative to the baseline. By 2015, the RFS adds 3.0 billion gallons corresponding to an increase of 25.1%.

3.4.2 Impacts on Land Markets

Table 3.2 decomposes the impact of the RFS on land markets, relative to the amount of corn acres under cultivation in the baseline, presented in the first row. The RFS drives up the amount of corn used in the economy, in proportion to the amount of ethanol added by the RFS in a given year. In 2011, this corresponds to an increase in the amount of corn acres harvested of 2.2% over the baseline. The bulk of this (three-quarters) comes from intra-cropland substitution—as the RFS drives up the price of corn relative to those of other crops, more cropland is shifted to corn production from other crops. These supply shifts coincide with reductions in demand for corn for domestic food production as well as reductions in export demand for all crops as the RFS drives up crop prices.

The remaining expansion in corn acreage results from a reduction in land allocated to CRP. Rising crop prices increase the net returns to cropland relative to the CRP rental subsidy which drives this decline. The *CRP interaction effect* hinges upon how much CRP is converted relative to the amount of ethanol added by the RFS. For every 1,000 equivalent gallons of ethanol added by the RFS, roughly one acre of CRP land is converted into cropland.[32] By 2015, the RFS drives up the amount of corn acres harvested by 5.8% relative to the baseline, with the shares from intra-cropland substitution and the conversion of CRP land remaining roughly the same.

[32] Equivalent gallons is the energy-content adjusted volume of ethanol or blended fuel relative to the energy content of gasoline. This conversion reflects the fact that ethanol and gasoline are treated as energy-equivalent substitutes in the production of blended fuel. See Appendix section C.4 for additional details.

3.4.3 Impacts on Import and Export Markets

Table 3.3 reports the impact of the RFS on crop export and crude oil import markets. Higher crop prices imply fewer crop exports. In 2011, exports for corn, soybeans, and wheat fall by 4.4%, 0.5%, and 2.2%, respectively. Domestic gasoline consumption falls in response to the RFS, resulting in a decline in crude oil imports of 0.4% in 2011. Reductions in both crop exports and crude oil imports increase in proportion to the amount of ethanol added by the RFS over time, with reductions in 2015 of 11.5%, 1.2%, 9.3%, and 0.9% in corn, soybean, and wheat exports and crude oil imports, respectively.

Reductions in crop exports and crude oil imports are the primary determinants of the *change in trade balance*. Reductions in crude oil imports leave more dollars in the US economy. Higher crop prices coupled with a reduction in exports on net corresponds to an increase in crop export receipts from abroad. In addition, changes in import and export markets impact the *blended fuel output effect*. Additional land is brought into cultivation in the rest of the world to offset reductions in crop exports. Falling crude oil prices cause rest of world demand for crude oil to increase, offsetting a portion of the decline in domestic consumption. Both adjustments correspond to additional GHG emissions.[33]

3.4.4 Impacts on Fuel Markets

Table 3.4 reports the impact of the RFS on fuel markets and vehicle miles travelled. The RFS causes the price of blended fuel to fall by 0.3% in 2011. As a result, the RFS causes blended fuel and vehicle-miles travelled to increase. For each equivalent gallon of ethanol added by the RFS, blended fuel consumption increases by 0.2 equivalent gallons and consequently only 0.8 gallons of gasoline are displaced domestically. As the price of blended fuel falls, so too does the per mile cost of driving, by roughly 0.2% in 2011 (panel three), corresponding to an additional 2.6 vehicle miles travelled for each equivalent gallon of ethanol added by the RFS. By 2015, the RFS results in a decline in the price of blended fuel of 0.7%, corresponding to

[33] Further details regarding how changes in these markets affect emissions are provided in the Appendix, section C.6.

an expansion in blended fuel of 0.1 equivalent gallons, displacement of 0.9 gallons of gasoline, and an increase in demand for vehicle miles travelled of 2.2 miles for each equivalent gallon of ethanol added by the RFS.

The fall in the price of blended fuel caused by the RFS impacts welfare in three important ways. Greater fuel and VMTm consumption cause the *blended fuel output effect* to imply a welfare loss instead of a benefit. In addition, less displacement of gasoline equates to a smaller reduction in crude imports which implies that the welfare gains from both the *oil premium effect* and the *change in the trade balance* will be smaller in magnitude.

3.4.5 Welfare Impacts

Table 3.5 decomposes the welfare effects of the RFS into the various terms in equation (3.3.24). The RFS results in a net welfare loss of \$564 million in 2011, when excluding the change in the trade balance. In contrast, when savings from the change in the trade balance of \$2,596 million are included, the RFS implies a net cost savings of \$2,032 million in 2011. Thus, whether the RFS results in a net welfare gain or loss depends critically on the magnitude of the change in the trade balance.[34] The next largest contributors to welfare in 2011 are: the *subsidy interaction effect*, the *oil premium effect*, the *blended fuel output effect*, *primary costs*, and the *CRP interaction effect* which entail costs of \$576 million, benefits of \$161 million, and costs of \$102 million, \$46 million, and \$1 million, respectively.

As more ethanol is added by the RFS in later years, land markets tighten and each additional EGG of ethanol added implies an ever greater increase in equilibrium ethanol and corn prices. This causes the change in the price of ethanol to more than double between 2011 and 2015 which impacts both the *blended fuel output effect* and *primary costs*, and causes greater reductions in import and export markets which in turn impacts the change in

[34]This is consistent with Cui et al. (2011) and Chen et al. (2012), although our assessment of the welfare gains from trade improves upon those estimates. Cui et al. (2011) considers just the gains from the corn export and crude oil import markets. Chen et al. (2012) consider the gains from the corn export market and the gasoline import market, which they attribute to the crude oil market. Our analysis includes the trade gains in all major crop export markets (corn, soybeans, wheat and cotton), as well as the crude oil import market.

the trade balance. Consequently, while the amount of ethanol added by the RFS more than doubles between 2011 and 2015, the *blended fuel output effect* and the *change in the trade balance* slightly outpace this doubling, and *primary costs* expand by roughly eight times. By 2015, the RFS implies a net cost of $1.6 billion when excluding the change in the trade balance and a net benefit of $6.4 billion when the change in the trade balance is accounted for.

The welfare gain from the change in the trade balance, while by far the largest component of welfare, must be considered with an important caveat. Our model is not a comprehensive model of international trade. For example, we do not incorporate endogenous adjustments in the exchange rate or other macroeconomic adjustments, nor do we explicitly model the pre-existing trade deficit which can drastically affect the welfare gains resulting from the change in the trade balance in the medium to long-run. Consequently, the welfare gain resulting from the change in the trade balance should be thought of as an upper bound of the true welfare gains from this channel. In fact, actual welfare gains from this channel may be much smaller.[35] Moreover, while the change in the trade balance reflects a distributional welfare gain from the perspective of the US, it corresponds to a decline in global welfare since it reflects the change in welfare that results due to the fact that the RFS effectively acts as an indirect non-tariff trade barrier. This is in sharp contrast to the other terms in equation (3.3.24) which reflect changes in economic efficiency. Given this, we prefer to emphasize those results that exclude the welfare gain from the change in the trade balance in what follows.

So far our analysis has ignored the costs of financing the change in government expenditures due to the RFS. Such financing costs are characterized by the marginal cost of public

[35]If the exchange rate were allowed to endogenously adjust in our model in order to restore trade balance (or the pre-policy trade deficit), the welfare gain resulting from the change in the trade balance would likely be much smaller. For example, Shapiro (2012) which uses a general equilibrium model where exchange rates (e.g. wage rates) are endogenous, finds that the gains from trade from a carbon tax are 80% lower than the case when the exchange rates are fixed. If the welfare gain from the change in the terms of trade of -$2,596 million in 2011 were dissipated by 80%, then the resulting welfare gain of -$519 million would be insufficient to offset the net costs from all other welfare components of $564 million.

funds. A marginal cost of public funds of 1.38 as reported in Bovenberg and Goulder (1996), effectively means that each dollar increase in expenditures requires $1.38 of revenue be raised to finance it. The fact that the marginal cost of public funds exceeds one owes to the fact that taxes must be levied to finance expenditures and those taxes distort the markets in which they are imposed. Once we account for the welfare cost from financing the change in government expenditures due to the RFS (assuming a marginal cost of public funds of 1.38), the central conclusions of our welfare analysis are largely unaffected. In 2011, net costs excluding the change in the trade balance increase by $271.1 million to $835.4 million, which is still roughly a third of the savings from the change in the trade balance.[36] In 2015, financing the change in government expenditures due to the RFS incurs an additional cost of $608.0 million, causing net costs excluding the change in the trade balance to increase to $2,210.5 million.

3.4.6 Does the RFS Pass a Benefit-Cost Test?

Table 3.6 reports a benefit-cost assessment of the RFS. When the change in the trade balance is excluded from our welfare analysis (panel one), the RFS fails a benefit-cost test, with a benefit-cost ratio far below one, or 0.35 to 0.28. This failure to pass a benefit-cost test is not at all exceptional. Across 2000 random draws of the external benefit parameters, the RFS passes the benefit-cost test at best 0.1% of the time. Net costs per equivalent gallon of ethanol added by the RFS range from $0.64 to $0.79.

In sharp contrast, when the change in the trade balance is included (panel three), the RFS results in a benefit-cost ratio that well exceeds one with a ratio between 3.4 to 3.9, and does so consistently, passing 100% of the time. Gross benefits now greatly outstrip gross costs, with net costs per equivalent gallon of ethanol added by the RFS of -$2.3 to -$3.2. The

[36] The change in government expenditures in 2011 is $438.7 million and equals the change in expenditures on the VEETC ($576.1 million) less the increase in fuel tax collections ($113.8 million) and less the change in CRP subsidy payments ($23.6 million). Applying a marginal cost of public funds of 1.38, causes net costs to increase by an additional $271.1 million. In 2013 and 2015, after accounting for these revenue raising costs, net costs excluding the change in the trade balance would instead be $1,345.3 million and $2,210.5 million, respectively, corresponding to additional revenue raising costs of $406.1 million and $608.0 million.

first panel of Table 3.7 reports what the minimum change in the terms of trade would need to be in order for the RFS to just pass a benefit-cost test. In 2015, this is \$1.5 billion which is roughly a quarter of the savings from the change in the trade balance that we observe.

3.4.7 The Trade-off Between Oil Dependency and Environmental Objectives

The second panel in Table 3.7 considers the trade-offs between the oil dependency and environmental objectives implied by the RFS. Our measure of these trade-offs is the change in net environmental external benefits, which is the sum of all the external environmental benefit terms included in equation (3.3.24), over the *oil premium effect*, reported as the mean over 2,000 random draws of all external benefit parameters.[37] This reflects the opportunity cost of using a single instrument to achieve two objectives. Every dollar reduction in the external costs of oil dependency that is achieved by the RFS implies negative environmental benefits (a cost) of \$0.90 in 2015. This is a key result of this paper, namely that policymakers trade-off environmental benefits almost dollar for dollar with oil dependency benefits. This trade-off emerges because the RFS causes the price of blended fuel to fall. Therefore, the numerator of net environmental benefits—which is dominated by the marginal external costs of blended fuel (MEC^F)—is positive. For example, three-fifths of the \$0.90 reduction in net environmental benefits results because of increase in the external costs of VMTm related externalities and another one-fifth because of an increase in the external costs of GHG emissions. This is further compounded by the fact that a fall in the price of gasoline means fewer gallons of gasoline are displaced, and so the *oil premium effect* in the denominator is smaller in magnitude.

3.4.8 The Implicit Value of Oil Dependency

The third panel in Table 3.7 reports the mean implicit value that policymakers place on the external costs of oil dependency (equation (3.3.25)) over 2,000 random draws of the vector of external cost parameters (excluding the oil premium). In 2015, we find that policymakers

[37] This computation does not require the change in the trade balance and so is the same irrespective of the change in the trade balance.

would need to value the external costs of oil dependency at \$1.11 per gallon of gasoline displaced in order for the RFS to pass a benefit-cost test. This is more than five times our central literature estimate of the oil premium, MEC^P, of \$0.22. A 90% confidence interval is also provided, showing that even in the most favorable case, the implicit value that policymakers place on oil dependency would need to be more than four times larger than the central literature estimate, or \$0.94. Recently, there has been some discussion as to whether there is a relationship between ethanol production and the prices of gasoline and crude oil, and by extension to our analysis, whether the RFS will have an impact on the price of blended fuel and the per-mile cost of driving.[38] Even if policymakers expected that the RFS would have no impact on the price of blended fuel and the per-mile cost of driving, the implicit value that policymakers place on oil dependency would still need to be exceptionally high, at \$0.99.[39]

3.4.9 Further Discussion: Swapping the VEETC for the RFS

Once EISA passed in 2007 some policymakers may have intended to eventually phase out the VEETC once the RFS was in place. We evaluate this case and find that if the RFS was intended to replace the VEETC, then the benefit-cost ratio improves to 0.85 to 0.88 when we exclude the change in the trade balance as reported in Table C.19 in the Appendix (panel one). Further, the RFS now passes the benefit-cost test roughly a quarter of the time over 2,000 random draws of the external cost parameters.

As reported in Table 3.8, swapping the VEETC for the RFS implies—not a trade-off between the environmental and oil dependency objectives of the RFS, but rather a mutual welfare gain with each dollar reduction in the external costs of oil dependency corresponding

[38] Du and Hayes (2009) finds that the growth in ethanol production between 1995 and 2008 was responsible for lowering the wholesale price of gasoline by \$0.07 to \$0.28 per gallon. Recently, Knittel and Smith (2012) challenge the results of Du and Hayes (2009) as well as extensions of this early work to later time periods (Du and Hayes, 2011) and (Du and Hayes, 2012), arguing that the relationship Du and Hayes identify is spurious.

[39] This calculation strips out from the *blended fuel output effect* the change in costs from the pre-existing fuel tax and the change in the external costs of VMTm related externalities (row four, first panel) both of which result because the prices of blended fuel and the per-mile cost of driving are allowed to adjust endogenously in our model.

to a net environmental benefit of \$1.3 to \$2.5. This occurs because the RFS now causes the price of blended fuel to increase since the removal of the VEETC ensures that the full increase in the price of ethanol caused by the RFS is passed through into the price of blended fuel. As before, VMTm related externalities are the largest component of net environmental benefits although now generating significant benefits instead of costs. GHG emissions also generate a small external benefit owing to the additional displacement of gasoline. As a result, the numerator of net environmental benefits reverses in sign, although this is partially offset by the larger oil premium in the denominator since more gasoline is displaced.

The implicit value that policymakers place on oil dependency is considerably lower at \$0.36 to \$0.42 per gallon of gasoline displaced as reported in the third panel of Table 3.8. This is still more than one and a half times greater than our central literature estimate of the oil premium, although now the 10^{th} percentile lower bound falls below zero. If we assume that the RFS has no impact on the price of blended fuel and the per-mile cost of driving, then the implied external costs of oil dependency increase to \$1.23 to \$1.39 largely because the increase in the price of blended fuel instead corresponds to a welfare improvement when the RFS replaces the VEETC.[40]

3.4.10 Implications for Advanced/Cellulosic Renewable Fuel Standards

So far the focus of this paper has been on corn-based ethanol. In this section we discuss the implications of our welfare analysis for the Advanced RFS. With respect to corn ethanol, we have observed that welfare is critically impacted through the change in the price of blended fuel induced by the RFS. The external benefits of GHG emissions are small relative to the external benefits from VMTm related externalities, although both move in the opposite

[40] This is the primary determinant of the improvement in the benefit-cost ratio in this case, but not the only one. In addition, swapping the VEETC for the RFS implies an additional welfare gain from not having to finance the tax credit. This is almost entirely offset by the fact that primary costs increase since the RFS results in a larger increase in the price of ethanol. These two terms alone imply a net welfare gain relative to the VEETC renewed case of -\$232 million in 2015. Price endogeneity in fuel markets implies a welfare gain from the blended fuel output effect of -\$793 million in 2015 and from the oil premium effect of -\$184 million in 2015. Thus, four-fifths of the welfare gain between the two scenarios results because of price endogeneity in fuel markets.

direction as the price of blended fuel. While many studies of advanced biofuels (Searchinger et al. (2008), EPA (2010)) anticipate significantly greater GHG emissions reductions as a result of the Advanced RFS, VMTm related externalities as mediated through the change in the price of blended fuel are likely to continue to be critical for the ability of the Advanced RFS to pass a benefit-cost test. To understand this, suppose that our results from our analysis of the RFS for conventional biofuels could also be extrapolated to the Advanced RFS, with the exception being the determination of the external benefits from GHG emissions which we instead assume yield emissions savings consistent with a composite of advanced biofuels.[41] Excluding the change in the trade balance, we find that net costs per equivalent gallon of advanced biofuel added would be \$0.13 lower in 2015 (from \$0.79) for our central case where the price of blended fuel falls, and \$0.09 lower when the RFS replaces the VEETC (from \$0.19) and the price of blended fuel increases. As a result, neither regime would pass a benefit-cost test, although we are very close for the regime when the RFS replaces the VEETC.

Whether the price of blended fuel increases or decreases will depend upon the rate at which the price of the advanced biofuel increases relative to the rate at which the price of gasoline decreases, conditional on the shares of biofuels in the production of blended fuel both before and after imposing the mandate. Using data from our model and the EIA's 2010 Annual Energy Outlook, as well as an estimate of the amount of cellulosic ethanol likely to be added by the Cellulosic RFS given cellulosic feedstock supply curves reported in the U.S. Department of Energy's Billion Ton Update (Perlack and Stokes, 2011), we can determine, for the Cellulosic RFS at least, a cut-off supply elasticity for cellulosic ethanol for which the change in the price of blended fuel will be zero.[42] The cut-off elasticity of 0.19

[41] Our composite biofuel in this case is a weighted share of the multiple types of advanced biofuels added by the advanced RFS in 2022 according to the EPA (2010) analysis. These are: cellulosic ethanol from switchgrass, cellulosic ethanol from corn residues, sugarcane ethanol, and biodiesel, with the first two types corresponding to 0.86 of advanced biofuels added in 2022 (EPA, 2010). For each advanced fuel type (except biodiesel), we consider the conversion pathway that results in the greatest emissions savings. The expected life-cycle emissions savings per unit of composite biofuel added, then, is just the share of each type multiplied by the 'best-case' life-cycle emissions savings for that type. See Appendix C.9 for additional details.

[42] This calculation is for the year 2022, when the Cellulosic RFS achieves its maximum. To determine the

that we identify is considerably lower than the average supply elasticity of 6.7 implied by the feedstock supply curves provided in the Billion Ton Update (Perlack and Stokes, 2011). Consequently, the Cellulosic RFS will likely cause the price of blended fuel to fall and thus likely fail a benefit-cost test.

3.5 Conclusion

This paper developed a multi-market economic model that integrated fuel, food and land markets and linked adjustments in these markets to the generation of environmental and oil dependency related externalities and accounted for several important pre-existing fiscal distortions. This framework has allowed us to isolate several key channels through which the RFS has impacted welfare and whether the RFS passes a benefit-cost test. We then used Monte Carlo sampling over external costs to infer how robust our central welfare results are, to understand policymakers' revealed trade-offs between the environmental and oil dependency objectives of the RFS, and what policymaker's implied value of the oil premium would have to be in order to justify the passing of the RFS.

We highlight several central findings. First, excluding the change in the trade balance, the RFS consistently fails a benefit-cost test with net costs totalling \$1.6 billion or \$0.79 per equivalent gallon of ethanol added by the RFS in 2015. If policymakers intended to replace the pre-existing ethanol subisidy with the RFS, then the RFS would pass a benefit-cost test a quarter of the time. Welfare gains from the change in the trade balance dominate all other components of welfare allowing the RFS to pass a benefit-cost test 100% of the time under either regime, although these savings are likely an upper bound of the actual welfare gains from this channel. Second, each dollar reduction in the external costs of oil dependency achieved by the RFS comes at the expense of additional environmental external costs of \$0.90, suggesting that policymakers trade-off the environmental objectives of the RFS with

amount of cellulosic ethanol likely to be added by the Cellulosic RFS we sum several feedstock supply curves for the year 2022 provided in the Billion Ton Update and impose a best estimate of the biomass to cellulosic ethanol conversion efficiency. See Appendix C.9 for additional details.

the oil dependency objectives almost dollar for dollar. If policymakers intended to swap the VEETC for the RFS, then environmental objectives instead coincide with oil dependency objectives, with each dollar reduction in oil dependency also providing $1.28 in net external environmental benefits. Third, policymakers would have to value the external costs of oil dependency at $1.11 per gallon of gasoline in order for the RFS to pass a benefit-cost test, which is more than five times our central literature estimate of the oil premium. This falls to $0.36 per gallon of gasoline or two times our central literature estimates if policymakers intended to let the VEETC expire.

In this study we have revealed several possible pathways that policymakers may have taken to support the RFS. Some policymakers may have sought to exploit the RFS to achieve strategic trade gains through the change in the trade balance, whereas others may have had an especially high valuation of the external costs of oil dependency. Still others, in anticipating the eventual repeal of the VEETC, may have had particularly strong environmental preferences.[43] These disparate pathways have uncovered an inherent ambiguity to our analysis of policymakers' intentions, which may have actually improved the ability of the RFS to pass. This is largely confirmed by the broad coalition that emerged to support EISA which achieved final votes of 86-8 in the US Senate and 314-100 in the House of Representatives.

This suggests that the decision to use a single instrument to achieve multiple objectives may have less to do with efficient instrument choice, but rather a desire to achieve legislative success given that some policymakers may have greater preferences or beliefs regarding one externality, market failure, or distributional objective than others. To the extent that such bundling of objectives occurs, however, there are likely to continue to be trade-offs between objectives such as the almost dollar for dollar trade-off between the environmental and oil dependency objectives of the RFS that we identify in this paper. Examining other

[43] Others may have had high distributional preferences for agricultural and/or ethanol producers as the RFS did increase incomes for these two groups. The focus of our analysis has been on the efficiency implications of the RFS and not the distributional implications and so do not speak to this channel here.

bundled policies through this lens, will provide additional opportunities to understand how policymakers balance these critical trade-offs and should be explored in future research.

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Table 3.1: Corn-based Ethanol Renewable Fuel Standard (RFS): Baseline and Mandated Quantities Over Time

	2003	2011	2012	2013	2014	2015
Corn-based Ethanol Baseline (billion G)	2.7	11.3	11.6	11.8	11.9	12.0
Mandated Quantities*	-	12.6	13.2	13.8	14.4	15.0
Difference Between Mandated and Baseline	-	1.3	1.6	2.0	2.5	3.0
% Difference in Estimated Mandate Relative to Baseline	-	11.3%	13.9%	16.7%	21.1%	25.1%
Corn-based Ethanol Baseline, no VEETC (billion G)	2.8	5.4	5.4	5.6	6.1	6.9

Notes: *: Estimate computed is based on a per gallon of blended fuel share mandate on ethanol consumption, which is calculated annually by taking the RFS statutory quantities and dividing by the expected blended fuel consumption for a given year. Prior to 2010, our model predicts that the amount of ethanol produced in the absence of the policy (the baseline) would exceed the amount mandated by the RFS, that is the RFS was not binding.

Table 3.2: Effects of the Corn-based Ethanol RFS on Land-Use

	2011	2013	2015
Baseline Corn (million acres)	83.7	83.8	82.5
% Change in Corn Acres Due to RFS	2.2%	4.3%	5.8%
Due to Intra-Cropland Substitution*	1.6%	3.2%	4.3%
Due to Adjustment in CRP	0.5%	1.1%	1.6%
Change in CRP (acres) Per EGG of Ethanol Mandated**	-0.001	-0.001	-0.001

Notes: All acres reported are harvested acres. *: Change in corn acres due to intra-cropland substitution reflects the reductions in soybean, wheat, hay, and cotton acres due to the RFS. **: An equivalent gallon of gasoline (EGG) is the energy-content adjusted volume of ethanol or blended fuel relative to the energy content of gasoline. Per EGG of ethanol mandated denotes normalization by the amount of ethanol added by the RFS.

Table 3.3: Effects of the Corn-based Ethanol RFS on Export and Import Markets

	2011	2013	2015
Corn Exports (billion bu)	1.92	1.95	1.92
% Change in Corn Exports	-4.4 %	-8.3 %	-11.5 %
Soybean Exports (billion bu)	1.20	1.26	1.29
% Change in Soybean Exports	-0.5 %	-0.6 %	-1.2 %
Wheat Exports (billion bu)	1.00	1.00	1.11
% Change in Wheat Exports	-2.2 %	-4.4 %	-9.3 %
Crude Oil Imports (billion bbls)	3.06	3.08	3.07
% Change in Crude Oil Imports	-0.4 %	-0.6 %	-0.9 %

Table 3.4: Effects of the Corn-based Ethanol RFS on Fuel Markets and Vehicle Miles Travelled

	2011	2013	2015
Baseline Price of Blended Fuel (in $/EGG)*	$2.24	$2.29	$2.42
% Change	-0.3%	-0.4%	-0.7%
% Due to the Increase in the Price of Ethanol	0.3%	0.6%	0.95%
% Due to the Decrease in the Price of Gasoline	-0.6%	-1.0%	-1.7%
Baseline Ethanol (Billion Equivalent Gallons Gasoline)	7.8	8.0	8.1
% Change in Ethanol Due to RFS	11.3%	16.7%	25.1%
Due to Displaced Gasoline	9.4%	14.6%	21.9%
Due to Additional Blended Fuel	1.9%	2.1%	3.2%
Gallons of Gasoline Displaced Per EGG of Ethanol Mandated	0.83	0.87	0.87
EGG of Blended Fuel Added Per EGG of Ethanol Mandated	0.17	0.13	0.13
Baseline Price of Miles (in $/mile)	$0.21	$0.22	$0.22
% Change	-0.2%	-0.2%	-0.2%
Change in VMT (miles) Per EGG of Ethanol Mandated	2.63	2.11	2.16

Notes: *: An equivalent gallon of gasoline (EGG) is the energy-content adjusted volume of ethanol or blended fuel relative to the energy content of gasoline. Per EGG of ethanol mandated denotes normalization by the amount of ethanol added by the RFS. The prices of blended fuel and miles are inclusive of the VEETC and the fuel tax.

Table 3.5: The Welfare Consequences of the RFS for Conventional Biofuels

	2011	2013	2015
Net Costs Excluding Change in Trade Balance (million $)	564.3	939.2	1,602.5
Net Costs Including Change in Trade Balance	-2,031.5	-3,670.5	-6,431.9
dW^{PC}, *Primary Cost*	45.6	145.7	360.8
dW^{E}, *Subsidy Interaction Effect*	576.1	892.2	1,357.7
dW^{F}, *Blended Fuel Output Effect*	102.2	156.5	270.4
External Benefits from Mileage Related Externalities	197.0	241.1	371.8
From Local Air Pollution	46.3	56.7	87.5
From Accidents	69.5	85.1	131.2
From Congestion	81.1	99.3	153.1
External Benefits from GHG Emissions	18.9	40.2	63.2
Fuel Tax Cost	-113.8	-124.8	-164.6
dW^{P}, *Oil Premium Effect* *	-160.8	-257.2	-388.2
dW^{N}, *CRP Interaction Effect*	1.3	2.0	1.7
CRP Related Externalities**	24.8	53.8	79.5
Reduction in CRP Rental Payments	-23.6	-51.9	-77.7
dW^{B}, *Change in Trade Balance*	-2,595.8	-4,609.8	-8,034.4

Notes: *: Benefits included in this category include the per gallon benefits from reduced military and geopolitical related expenditures, reduced crude oil price volatility, and reduced market power. **: External benefits to CRP land include benefits from wildlife (hunting and viewing), non-GHG air quality improvements, soil quality improvements, and recreation use benefits.

Table 3.6: Benefit-Cost Analysis of the RFS for Conventional Biofuels

	2011	2013	2015
Change in Ethanol Due to RFS (Billion Equivalent Gallons of Gasoline)*	0.9	1.3	2.0
Excluding Change in Trade Balance			
Net Costs (in million $)	564.3	939.2	1,602.5
Gross Costs	862.4	1,373.1	2,233.0
Gross Benefits	-298.1	-433.8	-630.5
Net Costs Per EGG of Ethanol Mandated ($ per EGG)	0.64	0.70	0.79
Net Costs Per EGG of Displaced Gasoline ($ per EGG)	0.77	0.80	0.90
Ratio of Gross Benefits to Gross Costs	0.35	0.32	0.28
Freq. By Which Gross Benefits Exceed Gross Costs**	0.1%	0.1%	0.0%
Including Change in Trade Balance			
Net Costs (million $)	-2,031.5	-3,670.5	-6,431.9
Gross Costs	862.4	1,373.1	2,233.0
Gross Benefits	-2,893.9	-5,043.6	-8,664.9
Net Costs Per EGG of Ethanol Mandated ($ per EGG)	-2.31	-2.74	-3.18
Net Costs Per EGG of Displaced Gasoline ($ per EGG)	-2.77	-3.14	-3.63
Ratio of Gross Benefits to Gross Costs	3.36	3.67	3.88
Freq. By Which Gross Benefits Exceed Gross Costs**	100.0%	100.0%	100.0%

Notes: *: An equivalent gallon of gasoline (EGG) is the energy-content adjusted volume of ethanol or blended fuel relative to the energy content of gasoline. Per EGG of ethanol mandated denotes normalization by the amount of ethanol added by the RFS. Per EGG of displaced gasoline denotes normalization by the amount of gasoline displaced by the RFS. **: Reflects the frequency by which gross benefits exceed costs across 2,000 Monte Carlo random draws of the vector of external benefits. See Appendix, Section C.8 for additional details. All other values reflect our central parameter estimates.

Table 3.7: Monte Carlo Simulations, RFS Added to Pre-existing VEETC

	2011	2013	2015
Change in Trade Balance Needed to Pass BC Test ($ billion)	-0.54	-0.90	-1.54
90 % Confidence Interval	*(-0.80, -0.33)*	*(-1.23, -0.59)*	*(-2.06, -1.06)*
Ratio of Net Environmental External Benefits to Ext. Ben. of Oil Dep.	-0.98	-0.90	-0.90
Ratio of VMT External Benefits to Ext. Ben. of Oil Dep.	-0.72	-0.55	-0.57
Ratio of GHG External Benefits to Ext. Ben. of Oil Dep.	-0.15	-0.20	-0.20
Ratio of CRP External Benefits to Ext. Ben. of Oil Dep.	-0.10	-0.14	-0.14
Freq. By Which Ext. Ben. of Oil Dep. Exceed Environmental External Benefits	0.0%	0.0%	0.0%
Ext. Ben. of Oil Dep. Required to Just Equal Env. Ext. Ben. ($ EGG)	-0.31	-0.27	-0.27
Implied External Costs of Oil Dependency ($ / EGG)			
Excluding Change in Trade Balance	0.98	1.01	1.11
90 % Confidence Interval	*(0.77, 1.29)*	*(0.84, 1.25)*	*(0.94, 1.36)*
Excluding Cost and External Benefit Categories Induced by $DR < 1$:			
Implied External Costs of Oil Dependency, Exc. $-t^F\left(\frac{dF}{d\theta}\right)$	1.13	1.11	1.20
Implied External Costs of Oil Dependency, Exc. $-t^F\left(\frac{dF}{d\theta}\right)$ and $MD^M\left(\frac{dM}{d\theta}\right)$	0.86	0.90	0.99
Including Change in Trade Balance	-2.57	-2.93	-3.44
90 % Confidence Interval	*(-2.78, -2.26)*	*(-3.10, -2.68)*	*(-3.61, -3.18)*
Excluding Cost and External Benefit Categories Induced by $DR < 1$:			
Implied External Costs of Oil Dependency, Exc. dW_R^{B}*	-0.08	-0.33	-0.49
Implied External Costs of Oil Dependency, Exc. dW_R^{B} and $-t^F\left(\frac{dF}{d\theta}\right)$	0.07	-0.22	-0.40
Implied External Costs of Oil Dependency, Exc. dW_R^{B}, $-t^F\left(\frac{dF}{d\theta}\right)$, and $MD^M\left(\frac{dM}{d\theta}\right)$	-0.20	-0.43	-0.61

Notes: Since oil dependency related externalities imply cost savings (benefit), negative numbers correspond to the ratio of benefits to cost. Medians, confidence intervals, and frequencies are reported over 2,000 Monte Carlo random draws of the vector of external benefits. See Appendix, Section C.8 for additional details. *: dW_R^{B} is the change in the trade balance resulting from crude oil imports; if the price of crude oil were fixed, this term would be zero.

Table 3.8: Monte Carlo Simulations, Pre-existing VEETC Replaced by RFS

	2011	2013	2015
Change in Trade Balance Needed to Pass BC Test ($ billion)	-0.26	-0.33	-0.32
90 % Confidence Interval	*(-1.00, 0.80)*	*(-1.15, 0.83)*	*(-1.14, 0.84)*
Ratio of Environmental External Benefits to Ext. Ben. of Oil Dep.	2.47	1.86	1.28
Ratio of VMT External Benefits to Ext. Ben. of Oil Dep.	2.19	1.91	1.37
Ratio of GHG External Benefits to Ext. Ben. of Oil Dep.	0.13	0.05	0.01
Ratio of CRP External Benefits to Ext. Ben. of Oil Dep.	-0.06	-0.10	-0.10
Freq. By Which Ext. Ben. of Oil Dep. Exceed Environmental External Benefits	13.8%	23.2%	38.5%
Ext. Ben. of Oil Dep. Required to Just Equal Env. Ext. Ben. ($ EGG)	0.55	0.42	0.29
Implied External Costs of Oil Dependency ($ / EGG)			
Excluding Change in Trade Balance	0.42	0.41	0.36
90 % Confidence Interval	*(-0.28, 0.89)*	*(-0.15, 0.78)*	*(-0.03, 0.62)*
Excluding Cost and External Benefit Categories Induced by $DR > 1$:			
Implied External Costs of Oil Dependency, Exc. $-t^F\left(\frac{dF}{d\theta}\right)$	0.79	0.85	0.88
Implied External Costs of Oil Dependency, Exc. $-t^F\left(\frac{dF}{d\theta}\right)$ and $MD^M\left(\frac{dM}{d\theta}\right)$	1.39	1.33	1.23
Including Change in Trade Balance	-4.01	-4.10	-4.34
90 % Confidence Interval	*(-4.71, -3.55)*	*(-4.66, -3.73)*	*(-4.74, -4.08)*
Excluding Cost and External Benefit Categories Induced by $DR > 1$:			
Implied External Costs of Oil Dependency, Exc. $dW_R^{\mathrm{B}*}$	-0.11	-0.38	-0.72
Implied External Costs of Oil Dependency, Exc. dW_R^{B} and $-t^F\left(\frac{dF}{d\theta}\right)$	0.27	0.06	-0.20
Implied External Costs of Oil Dependency, Exc. dW_R^{B}, $-t^F\left(\frac{dF}{d\theta}\right)$, and $MD^M\left(\frac{dM}{d\theta}\right)$	0.87	0.54	0.14

Notes: Since oil dependency related externalities imply cost savings (benefit), negative numbers correspond to the ratio of benefits to cost. Medians, confidence intervals, and frequencies are reported over 2,000 Monte Carlo random draws of the vector of external benefits. See Appendix, Section C.8 for additional details. *: dW_R^{B} is the change in the trade balance resulting from crude oil imports; if the price of crude oil were fixed, this term would be zero.

Appendix A

Appendix to How Disagreement Regarding Climate Change Affects Federal and State Efforts to Address It

A.1 Model Calibration

I calibrate the model to analyze the welfare impacts of ACESA for the year 2021. Although I calibrate the model for 2021, much of the data used to calibrate the economic model reflects the year 2007 economy which is then extrapolated forward to the year 2021 using data from the EPA's IGEM assessment of the ACESA climate bill and GDP projections from the US BEA.[1]

A.1.1 Economy

Economic Sector Definitions

I consider seven economic sectors: electricity, natural gas, heating oil, petroleum refineries, automotive, trade vulnerable industries, and other. These correspond to subscripts $s = 1, ..., 7$, respectively.

Electric power generation, transmission and distribution is listed as NAICS=221100. I define this as $s = 1$, *Electricity*.

Natural gas distribution is listed as NAICS=221200. I define this as $s = 2$, *Natural Gas*.

Heating Oil dealers is listed as NAICS=454311. Liquefied Petroleum Gas (Bottled Gas) Dealers is listed as NAICS=454312. Other Fuel Dealers is listed as NAICS=454319. I define this as $s = 3$, *Heating Oil*.

Petroleum refineries is listed as NAICS=324110. I define this as $s = 4$, *Petroleum Refineries*.

Automobile manufacturing is listed as NAICS=336111. Light truck and utility vehicle manufacturing is listed as NAICS=336112. Heavy duty truck manufacturing is listed as NAICS=336120. Motor vehicle body manufacturing is listed as NAICS=336211. Motor vehicle parts manufacturing is listed as NAICS=336300. I define this as $s = 5$, *Automotive*.

Alkalies and chlorine manufacturing is listed as NAICS=325181. All other basic inorganic chemical manufacturing is listed as NAICS=325188. All other basic organic chemical

[1] While 2008 or 2009 are closer to the ACESA vote, 2007 precedes the recent recession.

manufacturing is listed as NAICS=325199. Alumina refining is listed as NAICS=331311. Carbon and graphite product manufacturing is listed as NAICS=335991. Carbon black manufacturing is listed as NAICS=325182. Cellulosic organic fiber manufacturing is listed as NAICS=325221. Cement manufacturing is listed as NAICS=327310. Ceramic wall and floor tile manufacturing is listed as NAICS=327122. Clay refractory manufacturing is listed as NAICS=327124. Copper, nickel, lead, and zinc mining is listed as NAICS=21223. Cyclic crude and intermediate manufacturing is listed as NAICS=325192. Electrometallurgical ferroalloy product manufacturing is listed as NAICS=331112. Ethyl alcohol manufacturing is listed as NAICS=325193. Flat glass manufacturing is listed as NAICS=327211. Glass container manufacturing is listed as NAICS=327213. Ground or treated mineral and earth manufacturing is listed as NAICS=327992. Gum and wood chemical manufacturing is listed as NAICS=325191. Inorganic dye and pigment manufacturing is listed as NAICS=325131. Iron and steel mills is listed as NAICS=331111. Iron and steel pipe and tube manufacturing from purchased steel is listed as NAICS=331210. Iron ore mining is listed as NAICS=212210. Lime manufacturing is listed as NAICS=327410. Mineral wool manufacturing is listed as NAICS=327993. Newsprint mills is listed as NAICS=322122. Nitrogenous fertilizer manufacturing is listed as NAICS=325311. Noncellulosic organic fiber manufacturing is listed as NAICS=325222. Nonclay refractory manufacturing is listed as NAICS=327125. Other pressed and blown glass and glassware manufacturing is listed as NAICS=327212. Other structural clay product manufacturing is listed as NAICS=327123. Paper (except newsprint) mills is listed as NAICS=322121. Petrochemical manufacturing is listed as NAICS=325110. Phosphate rock mining is listed as NAICS=212392. Phosphatic fertilizer manufacturing is listed as NAICS=325312. Plastics material and resin manufacturing is listed as NAICS=325211. Porcelain electrical supply manufacturing is listed as NAICS=327113. Primary aluminum production is listed as NAICS=331312. Primary smelting and refining of copper is listed as NAICS=331411. Primary smelting and refining of nonferrous metal (except cooper and aluminum) is listed as NAICS=331419. Pulp mills is listed as NAICS=322110. Reconstituted wood product manufacturing is listed as NAICS=321219. Synthetic organic dye and pigment manufacturing is listed as NAICS=325132. Synthetic rubber manufacturing is listed as NAICS=325212. Tire cord and tire fabric mills is listed as NAICS=314992. Vitreous china plumbing fixture and china and earthenware bathroom accessories manufacturing is listed as NAICS=327111. Vitreous china, fine earthenware, and other pottery product manufacturing is listed as NAICS=327112. Wet corn milling is listed as NAICS=311221. I define this as $s = 6$, *Trade Vulnerable Industries*. This characterization of Trade Vulnerable Industries is taken from Schneck et al 2009.

Non-differentiated capital is the total amount of capital less capital from these six sectors. I define this as $s = 7$, *Other Economic*.

Civic Sector Definitions

I permit seven categories of civic 'sectors' to reflect the seven broad categories of permits otherwise distributed by ACESA after those provided to the economic sectors I have defined above. *Low Income* reflects permits going to low-income consumers, or $s = 8$. *CCS* reflects permits going to Carbon Capture and Storage (CCS) beneficiaries, or $s = 9$. *Renewables* reflects permits going to areas with high potential for renewable energy development, or $s = 10$. *Adaptation* reflects permits going for domestic adaptation, or $s = 11$. *Workers* reflects permits going for job re-training and other worker investments, or $s = 12$. *Building* reflects permits going for building codes, or $s = 13$. *Other Civic* reflects permits going for international forestry set-asides, wildlife and natural resource adaptation, international adaptation, international clean technology deployment, and for deficit reduction and climate change consumer refund, or $s = 14$.

Size of the Economy

I assume total US Real GDP equal to $19,519.5 billion (2009 dollars) in 2021. This is computed after first calculating an average annual growth Real GDP rate over the past 20 years (2012-1992) of 2.62% from the *US BEA Real GDP, Table 1.1.6* dataset and extrapolating this from the total real GDP reported in 2012 of \$15,470.7 billion. I note that the EPA's IGEM Analysis of ACESA reports GDP equal to \$19,173.0 billion (after adjusting to 2009 dollars) in 2020. The EPA estimate is roughly 0.8% higher than the same calculation performed for the year 2020. The US CBO's *The Budget and Economic Outlook: Fiscal Years 2011-2021* reports a GDP estimate of \$23,333.8 in 2021 (after adjusting to 2009 dollars), which is 19.5% greater than my estimate.

To determine the share of capital and labor in the economy I use the US BEA *2002 Input-Output Table, The Use of Commodities by Industries after Redefinitions*. I compute a share of labor income to total output, $share_{\pi_0}$, equal to 0.3179 which equals 'Compensation of employees' divided by 'Total industry output'. I assume the share of capital to total output equal to $1 - share_{\pi_0}$. Using this the total value of labor nationally, π_0, is \$6,204.5 billion in 2021 ($GDP_{2021} share_{\pi_0}$). Likewise, the total value of capital nationally, rK_0, is \$13,315.0 billion ($GDP_{2021}\left(1 - share_{\pi_0}\right)$). Normalizing $r = 1$, then K_0 is 13,315.0.

Labor

$\bar{L}_d$ is the sum of persons sixteen or older who are in the civilian labor force as reported by the *US Census 2007 American Community Survey, DP-03 Selected Economic Characteristics, 1-Year Estimates* by congressional district.

Total returns to labor by congressional district, π_d, is computed by combining employment data by two digit NAICS code provided in the *US Census 2007 American Community Survey, DP-03 Selected Economic Characteristics, 1-Year Estimates* by congressional district with national data on compensation to employees by three digit NAICS code provided in the *US BEA 2002 Input-Output Table After Redefinitions, Use File*. Formally, π_d equals:

$$\pi_d = \pi_0 \sum_{\hat{s}=1}^{13} comp_{\hat{s}} \sigma_{d\hat{s}}, \tag{A.1.1}$$

where $comp_{\hat{s}}$ is "compensation to employees" by two-digit NAICS code $\hat{s} = 1, ..., 13$ aggregated from data by three digit NAICS codes reported in the BEA dataset, and $\sigma_{d\hat{s}}$ is the share of employees in sector $\hat{s}$ in congressional district d to the total number of employees in sector $\hat{s}$ nationally which is computed from the Census dataset. Formally, this is:

$$\sigma_{d\hat{s}} = \frac{emp_{d\hat{s}}}{\sum_{\hat{s}=1}^{13} emp_{d\hat{s}}}, \tag{A.1.2}$$

where $emp_{d\hat{s}}$ is the total number of employees in congressional district d employed in two-digit NAICS sector $\hat{s}$.

Capital

Detailed capital data by congressional district and sector does not exist. I approximate capital demanded by district d for sector s according to:

$$k_{ds} = \varrho_{ds} k_s, \tag{A.1.3}$$

where k_s is total amount of capital nationally in sector s, and ϱ_{ds} is the share of capital in district d and sector s to the total amount of capital in sector s nationally.

δ_{ds} is given by:

$$\varrho_{ds} = \frac{x_{ds}}{\sum_{d=1}^{D} x_{ds}}, \tag{A.1.4}$$

where x_{ds} equals the estimated total number of employees in congressional district d and economic sector s.

x_{ds} is computed using the *US Census 2007 County Business Patterns* dataset which has data at the county level on employment, total annual payroll, and number of establishments by employment size class broken down by six-digit NAICS codes. Out of a dataset of 2,216,770 counties by NAICS sectors, data on employment (mid-March) exists for only 741,178 county by NAICS classes and total annual payroll for only 930,409 county by NAICS classes. The missing datapoints in this series are those that are withheld to avoid disclosing confidential firm data, and both the employment and total annual payroll variables separately provide a noise flag denoting this fact ($nf = D$), with the value for the respective variable set to 0 when that this is the case. That said, the number of establishments by employment size class is not confidentially protected and appears to be complete (see below). Thus I impute x_{ds} using an estimate of total employment by county and economic sector, $\hat{emp}_{cs}$, using the number of establishments by size class dataseries, and the share of area of county c in congressional district d, s_{cd}. Thus x_{ds} is given by:

$$x_{ds} = \sum_{c} s_{cd}\hat{emp}_{cs}. \tag{A.1.5}$$

My estimate of the total number of employees by county, $\hat{emp}_{cs}$ is given by:

$$\begin{aligned}\hat{emp}_{cs} = {} & n_{(1-4)}2.5 + n_{(5-9)}7 + n_{(10-19)}15 + n_{(20-49)}35 + n_{(50-99)}75 + n_{(100-249)}175 \\ & + n_{(250-499)}375 + n_{(500-999)}750 + n_{(1000-1499)}1250 + n_{(1500-2499)}2000 + n_{(2500-4999)}3750 \\ & + n_{(5000+)} * 6000, \end{aligned} \tag{A.1.6}$$

where $n_{(1-4)}$ is the number of establishments with $1 - 4$ employees, and the other n_x are likewise defined with $n_{(5000+)}$ being the number of establishments with 5,000 plus employees. I note that unlike my estimate of the number of employees by county-NAICS combination, emp_{cs}, $\hat{emp}_{cs}$ appears to be complete. That is, for all county-NAICS combinations $\hat{emp}_{cs}$ does not equal zero. I can validate this estimate of the number of employees by county-NAICS combination by comparing $\hat{emp}_{cs}$ with emp_{cs} for those datapoints that do not have a confidentiality noiseflag (e.g. $nf \neq D$). For this subset I find that $\hat{emp}_{cs}$ has a mean of 954.4 and a standard deviation of 11,210.0 and emp_{cs} a mean of 848.6 and a standard deviation of 10,259.9, with the average difference between the two equal to 105.8, or $\hat{emp}_{cs}$ is on average 12.5% greater than emp_{cs}. Although there is some error in $\hat{emp}_{cs}$, this error is not excessive and the correlation coefficient between $\hat{emp}_{cs}$ and emp_{cs} equals 0.9913, suggesting that $\hat{emp}_{cs}$ should be a decent proxy for emp_{cs}. I note that across all counties in the US the sum of $\hat{emp}_{cs}$ for the NAICS code representing the economy-wide total number of employed in the US is 135.0 million, whereas according to the national *2007 County Business Patterns* dataset the total number employed in the US economy in 2007 was 120.6 million. Finally, since I do not have all county-NAICS combinations in the data, those combinations that are not present are assumed to have zero employees for the NAICS sector for that respective county.

The share of county c in district d is given by:

$$s_{cd} = \frac{\text{area of county } c \text{ in district } d}{\text{area of county } c}, \tag{A.1.7}$$

where areas are computed using ESRI's ArcGIS software using shapefiles for congressional districts and counties provided by the US Census.

Capital going to sector s nationally is given by:

$$k_s = \chi_s K_0, \tag{A.1.8}$$

where χ_s is the share of the value of all commodities sold by sector s nationally to the total value of all commodities in the economy.

χ_s is computed using data from the *US BEA 2002 Input-Output Tables, Detailed Make File* which provides data on the total value of commodities produced nationally by six digit NAICS sector. That is:

$$\chi_s = \frac{\text{Total Commodity Value}_s}{\sum_{s=1}^{7} \text{Total Commodity Value}_s}. \tag{A.1.9}$$

where Total Commodity Value$_s$ is the total value of the commodity produced by economic sector s in producers' prices. The BEA dataset does not report the annual sales of heating oil dealers, LPG dealers, or other fuel dealers, which I have defined as my third economic sector, *Heating Oil*. As a result, I impute the share of Home Heating Oil, $\chi_{s=3}$, using the size of the electricity sector from the *US BEA 2002 Input-Output Tables*, $\chi_{s=1}$, data from the EIA on the share of BTU's used for home heating oil relative to those used for electricity generation, $BTUshare_{HHOtoElect}$. In 2007, the electric power sector consumed 40,068 trillion BTUs according to the *US EIA 2012 Annual Energy Review Table 8.4b*. The *US EIA 2012 Annual Energy Review Table 5.12* reports that 8,921 trillion BTUs, 67 trillion BTUs, and 1,729 trillion BTUs of distillate fuel oil, kerosene, and propane were supplied in 2007. According to the *US EIA Fuel Oil and Kerosene Sales 2009* the share of distillate fuel oils sales to the residential sector was 0.081 in 2007. This reflects the proportion of total distillate fuel that is going for home heating oil, i.e. distillate fuel oil #2. Likewise, the same report shows that 0.66 of kerosene sales went for residential use in 2007. Using these shares and the information on BTUs supplied I calculate $BTUshare_{HHOtoElect} = \frac{(8921*0.081+67*0.66+1729)}{40068} = 0.0623$. Consequently, $\chi_{s=3}$ is given by:

$$\chi_{s=3} = BTUshare_{HHOtoElect}\chi_{s=1}. \tag{A.1.10}$$

Finally, $\chi_{s=7} = 1 - \sum_{s=1}^{6} \chi_s$. Together, these calculations imply: $\boldsymbol{\chi} = [0.0151359, 0.0056347, 0.000943, 0.0115895, 0.0267711, 0.0243214, 0.9156044]$.

Given k_{ds} total capital demanded by congressional district is simply: $y_d = \sum_{s=1}^{7} k_{ds}$.

Private Good Production Parameters

Under no policy, representative firms located in each district solve (1.4.6).

The solution to (1.4.6) provides the unconditional factor demands, $y_d\left(r; \gamma_d, \rho_d, \bar{L}_d, \sigma\right)$, and the value function is the total returns to labor, $\pi_d\left(r; \gamma_d, \rho_d, \bar{L}_d, \sigma\right)$. Inverting the closed form solutions corresponding to $y_d\left(r; \gamma_d, \rho_d, \bar{L}_d, \sigma\right)$ and $\pi_d\left(r; \gamma_d, \rho_d, \bar{L}_d, \sigma\right)$, given my calibration year data, r, π_d, y_d, the capital share parameter for the CRS CES production function,

ρ_d, has a closed form solution that is given by:

$$\rho_d = \frac{\left(\left(\bar{L}_d^{\sigma}\right)(rK_d)\right)}{\left(\pi_d\left(y_d^{\sigma}\right) + \left(\bar{L}_d^{\sigma}\right)(rK_d)\right)}. \tag{A.1.11}$$

Given ρ_d, $y_d\left(r;\gamma_d,\rho_d,\bar{L}_d,\sigma\right)$, and calibration year data, $r, y_d, \bar{L}_d$, I can obtain the closed form solution for the scaling parameter:

$$\gamma_d = \frac{(\pi_d + rK_d)}{\left(\rho_d\left(y_d^{\sigma}\right) + (1-\rho_d)\left(\bar{L}_d^{\sigma}\right)\right)^{\left(\frac{1}{\sigma}\right)}}. \tag{A.1.12}$$

Finally, given k_{ds} and y_d, I can compute the Leontief share parameters: $\omega_{ds} = \frac{k_{ds}}{y_d}$. I select σ such that the difference between the business as usual GDP $\left(\sum_{d=1}^{D}(x_d - \kappa_d)\right)$ and GDP under the 2021 ACESA cap $\left(\sum_{d=1}^{D}\left(x_d^{WM} - \kappa_d^{WM} - \kappa_d^{H,WM}\right)\right)$ equals the GDP loss predicted by the EPA's IGEM Scenario 2 analysis of ACESA of \$100.8 billion (2009 \$) for 2021. The original value is \$98.0 billion (2000 \$), which after adjusting for 2009 \$, comes to \$121.9 billion. Subtracting \$-21.1 billion worth of banked permits in 2021 provides the final figure.

Capital Supply Parameters

I assume capital supply is equal to capital demand by congressional district, $K_s = y_d$.

I select η such that the permit price predicted by my model under the 2021 ACESA cap approximates the estimated permit price reported in the *US EPA IGEM Analysis*, Scenario 2 of $P = \$16.75$ per ton CO_2e. Finally, the capital supply scaling parameter can be solved as a function of the calibrated data:

$$\zeta_j = rK_j^{\left(-\frac{1}{\eta_j}\right)}. \tag{A.1.13}$$

A.1.2 Emissions

The data used to calibrate emissions by sector comes from the *US EPA Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2010 Table ES-2* for the year 2007. This provides emissions from various sources which I aggregate to compute emissions by economic sector. I then re-scale these emissions levels to the emissions levels predicted by the *US EPA IGEM Analysis* for the year 2021.

Total net emissions in the US in 2007 were 7,263.2 Tg CO_2e. Total predicted emissions under the EPA analysis are 7,448.8 Tg CO_2e. Of these 1,413.2 Tg CO_2e or 19.0% of total emissions in 2021 are projected to be outside of the cap, leaving total covered emissions of 6,035.6 Tg CO_2e. If I assume that 19.0% of 2007 emissions are emissions that would not be covered given the 2021 coverage levels, the net emissions in 2007 would be 5,885.2 Tg CO_2e ($= (1-0.19)7,263.2$). This allows us to rescale 2007 emissions to 2021 levels according to $share_{emissions} = \frac{6{,}035.6}{5{,}885.2} = 1.026$.

Emissions for sector *Electricity* equal CO_2 emissions from fossil fuel combustion for electricity generation plus SF_6 from electrical transmission and distribution = 2,412.8 + 8.8 = 2,421.6 Tg CO_2e, which after rescaling are 2,483.5 Tg CO_2e.

Emissions for sector *Natural Gas* equals CO_2 emissions from natural gas systems, plus CH_4 from natural gas systems = 30.9 + 168.4 = 199.3 Tg CO_2e, which after rescaling are 204.4 Tg CO_2e.

Emissions for sector *Heating Oil* equals CO_2 emissions from non-energy use of fuels = 134.9 Tg CO_2e, which after rescaling are 138.3 Tg CO_2e.

Emissions for sector *Petroleum Refineries* equals CO_2 emissions from petrochemical production and petroleum systems plus CH_4 from petroleum systems and petrochemical production = 4.1+0.3 + 29.8+3.3 = 37.5 Tg CO_2e, which after rescaling are 38.5 Tg CO_2e.

Emissions for sector *Automobiles* is set equal to zero. I note that the EPA's Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2010 does report the emissions from fossil fuel combustion for transportation in the US of 1,904.7 Tg CO_2e. However, this is emissions from non-point sources and so it does not make sense to attribute emissions to automobile production, which is how the sector is categorized here.

Emissions for sector *Trade Vulnerable Industries* equals CO_2 emissions from iron, steel and metallurgical coke production, cement production, lime production, ammonia production, aluminum production, soda ash production and consumption, titanium dioxide production, ferroalloy production, glass production, zinc production, phosphoric acid production, lead production, and silicon carbide production and consumption plus CH_4 from iron, steel, and metallurgical coke production, ferroalloy production, and silicon carbide production and consumption plus N_2O from nitric acid production and adipic acid production plus HFC's from semiconductor manufacture plus PFC's from semiconductor manufacture and aluminum production plus SF_6 from magnesium production and processing and semiconductor manufacture = 71.3 +44.5 +14.6 +9.1 +4.3 +2.9 +1.9 +1.6 +1.5 +1.0 +1.2 +0.6 +0.2 +0.7 +0.05 +0.05 +19.7 +10.7 +0.3 +3.8 +3.8 +2.6 +0.8 = 197.2 Tg CO_2e, which after rescaling are 202.2 Tg CO_2e.

Emissions for *Other Economic Sectors* equals total net emissions of 7,263.2 Tg CO_2e less emissions from the above sectors, so = 7,263.2 - 2,421.6 - 199.3 - 134.9 - 37.5 - 197.2 = 4,272.7 Tg CO_2e. After rescaling to 2021 emissions levels I have 4,381.9 Tg CO_2e. From this I deduct the emissions that are not covered by the cap, 1413.2 Tg CO_2e, leaving 2,968.7 Tg CO_2e. These are the emissions that enter the model.

Thus, other emissions is 58.8% of total emissions, and emissions from the other six sectors are 41.2% of total emissions. While the six formal sectors receive 62% of total permits in 2021, it should be noted that given the limited way in which the *Inventory* reports sectoral emissions it is virtually impossible to disentangle the emissions from industrial sources that are generated by the six formal sectors versus those generated by industrial sources embedded with the other sector.

Let E_s denote the emissions levels defined above. Then the sectoral emissions parameters are simply $\alpha_s = \frac{E_s}{k_s}$.

Emissions Validation

Given capital by district and sector, k_{ds} and the sectoral emissions parameters, α_s, I am able to impute total emissions by district, $E_d = \sum_{s=1}^{7} \alpha_s k_{ds}$. To validate this imputation I consider two alternative emissions datasets, the *US Vulcan Emissions, Version 2.2* dataset which provides emissions estimates by 10km squares across the US for 2007, and the *US EPA Greenhouse Gas Reporting Program 2010* which began monitoring emissions from direct emitters and suppliers in the US beginning in 2010, which together account for 85% to 90% of total US emissions. Using GIS software I compute estimates of total emissions by congressional district from each dataset.[2] Re-scaling all three estimates by the total emissions predicted in each dataset, respectively, provides the share of total emission by congressional district, which I use for comparison.[3] My imputed emissions estimate exceeds the *Vulcan* estimate on average by 10.4% and under-predicts the *Greenhouse Gas Reporting Program* estimate on average by 3.1%. Standard deviations are considerable at 61.4% and 176.9% for each dataset, respectively. While these standard deviations are considerable, a direct comparison of both validation datasets provides some basis for understanding these magnitudes. The emissions intensity predicted by the *Greenhouse Gas Reporting Program* estimate exceeds the *Vulcan* estimate by 8.1% on average with a standard deviation of 152.4%. Thus, differences in coverage likely explain a great deal of this difference.

[2]Emissions by congressional district using the *Vulcan* dataset are computed by intersecting the 10km squares with my shapefile of congressional districts, and then summing emissions by 10 km square by the fraction of area overlap in each district. The *Greenhouse Gas Reporting Program* provides the latitude and longitude coordinates for 6,232 direct emitters ("facilities that combust fuels or otherwise put GHGs into the atmosphere directly from their facility") and 759 suppliers ("those entities that supply certain fossil fuels or fluorinated gases into the economy which, when combusted, released or oxidized emit greenhouse gases into the atmosphere"). After plotting each facility I join facilities with the congressional district to which they are located, and then sum total emissions across facilities located within each congressional district.

[3]I note that there is significant differences in coverage between the three datasets and in some cases different years of coverage, making direct comparisons difficult. By rescaling by total emissions predicted by each dataset what I am comparing is the share of total emissions by congressional district to the total emissions predicted nationally, or the relative emissions intensity of each congressional district predicted by each dataset.

A.1.3 Civil Sector Exposure

Low Income Exposure

Low Income exposure reflects the share of households in a congressional district whose incomes in the last 12 months are below the poverty level to total US households whose incomes in the last 12 months are below the poverty level. This is simply:

$$\delta_{d,s=8} = \frac{poor_d}{\sum_{d=1}^{D} poor_d}, \tag{A.1.14}$$

where $poor_d$ is the number of households in congressional district d whose income in the past 12 months has been below the poverty level as reported in the *US Census 2007 American Community Survey*.

CCS Exposure

CCS exposure reflects the share of potential carbon, capture and storage available in a congressional district to total US potential for carbon, capture and storage. This is simply:

$$\delta_{d,s=9} = \frac{CCS_d}{\sum_{d=1}^{D} CCS_d}, \tag{A.1.15}$$

where CCS_d is the metric tons of CCS potential in congressional district d.

To compute CCS_d I merge data from the three principal datasets that are used by NREL to compute the CCS estimates reported in *US NREL 2012 Carbon Utilization and Storage Atlas*. These three datasets are: *US NREL 2012 National Carbon Sequestration Database and Geographic Information System (NATCARB) Saline 10K*, *US NREL 2012 NATCARB Coal 10K*, and *US NREL 2012 NATCARB Oil and Gas 10K* spatial databases. While the Atlas also discusses the CCS potential of sedimentary basins, basalt formations, and organic-rich shale basins, the *Atlas* does not provide estimates of CCS potential for these geologies. For the three geologies for which I do have CCS potential estimates by congressional district, I sum to compute an estimate of total CCS potential for each congressional district d given by:

$$CCS_d = CCSSaline_d + CCSCoal_d + CCSOil_d. \tag{A.1.16}$$

To compute $CCSSaline_d$ I intersect the *Saline 10K* spatial database with my shapefile of congressional districts to construct saline formation (subscript n) by congressional district geographies which I denote by the subscript dn. Saline formations are layers of sedimentary porous and permeable rocks saturated with salty water called brine that are suitable for CCS. My estimate of the carbon potential from saline formations by congressional district is given by:

$$CCSSaline_d = \sum_n \left(\frac{CCSSaline_d area_{dn}}{\sum_n area_{dn}} \right), \tag{A.1.17}$$

where $CCSSaline_d$ is the medium (P50) estimate of carbon storage potential in metric tonnes for each saline geography n if suitability class equals 1, and $area_{dn}$ is the area of intersected geography dn. For those saline geographies with a 0 value for the medium (P50) estimate I impute this variable as the mean of the P10 and P90 estimates for each saline geography n.

I use repeat this technique to acquire $CCSCoal_d$ and $CCSOil_d$, using the *Coal 10K* and *Oil and Gas 10K* spatial databases, respectively. $CCSCoal_d$ reflects the CCS potential from coal that is considered unmineable because of geologic, technological, and economic factors (typically too deep, too thin, or lacking the internal continuity to be economically mined with today's technologies). $CCSOil_d$ reflects the CCS potential of oil and gas reservoirs, that is porous rock formations (usually sandstones or carbonates) containing hydrocarbons (crude oil and/or natural gas) that have been physically trapped.

Renewables Exposure

Renewables exposure reflects a weighted composite of projected renewables by congressional district for the year 2021. Formally, define:

$$\delta_{d,s=10} = \frac{renew_d}{\sum_{d=1}^{D} renew_d}, \tag{A.1.18}$$

where $renew_d$ is a composite of total renewable potential in congresional district d in 2021. (A.1.18) reflects a simple normalization of $renew_d$ so that exposure sums to 1 across all congressional districts. Formally, $renew_d$ is given by:

$$renew_d = s_{geo} geo_d + s_{sol} sol_d + s_{wind} wind_d + s_{bio} bio_d, \tag{A.1.19}$$

where s_{geo}, s_{sol}, s_{wind}, and s_{bio} are the shares of geothermal, solar, wind and biomass, respectively, of total renewables (the sum of all four) anticipated by 2021. The variables geo_d, sol_d, $wind_d$, and bio_d are measures of the geothermal, solar, wind and biomass potential in congressional district d, respectively, to the total amount available in that renewable class available nationally.

The variables s_{geo}, s_{sol}, s_{wind}, and s_{bio} are impute using data from *US EIA 2012 Annual Energy Review, Table 10.1* which provides the amount of geothermal, wind, solar, and total biomass consumed from 1949 to 2010. I use this data to compute the percent annual growth rate for each year between 1990 and 2010. I then take the average annual growth rate over this 20 year period and use this to impute the total amount of biomass, geothermal, wind, and solar produced by 2021, given the most recent 2011 projections also provided in the table. Given these imputations I calculate weights that reflect the share of a particular renewable class to total renewables consumed in 2021 or s_{geo}, s_{sol}, s_{wind}, and s_{bio}. These shares are 0.019, 0.018, 0.581, and 0.383 for geothermal, solar, wind, and biomass respectively.

To compute wind potential by congressional district d, $wind_d$, I first merge *US NREL*

2011 Alaska Wind 25 km shapefile with the *US NREL 2011 Hawaii Wind 25 km* and the *US NREL 2011 Lower 48 Wind 25 km* shapefiles. The geographies n in the combined US shapefile each possess a wind power class that corresponds to the intensity of wind exposure at 25 km height above the surface. Next, I intersect the resulting US Wind 25 km shapefile with my shapefile of congressional districts, resulting in a new shapefile of power class by congressional district geographies dn. Finally $wind_d$ is given by:

$$wind_d = \frac{\sum_n area_{dn}^{pc\geq 3}}{\sum_{d=1}^{D} \sum_n area_{dn}^{pc\geq 3}}, \tag{A.1.20}$$

where $area_{dn}^{pc\geq 3}$ is the area of geography dn that has a wind powerclass of 3 or greater, which according to NREL reflects areas "are suitable for most utility-scale wind turbine applications" (US National Renewable Energy Laboratory, 2013). The estimate of wind potential by congressional district, $wind_d$, is thus simply the share of total wind potential in a congressional district to the sum of all total wind potential in the US.

To compute biomass potential by congressional district d, bio_d, I first merge *US NREL 2012 Urban Wood and Secondary Mill Residues* shapefile with *US NREL 2008 Crop Residues* shapefile and *US NREL 2008 Forest and Primary Mill Residues* shapefile. I use this to compute the total amount of biomass energy available from crop residues, methane emissions from manure management, methane emissions from landfills and wastewater treatment facilities, forest residues (forest residues include logging residues and other removable material left after carrying out silviculture operations and site conversions), primary and secondary mill residues (primary mill residues include wood materials (coarse and fine) and bark generated at manufacturing plants (primary wood-using mills) when round wood products are processed into primary wood products, such as slabs, edgings, trimmings, sawdust, veneer clippings and cores, and pulp screenings; secondary mill residues include wood scraps and sawdust from woodworking shops - furniture factories, wood container and pallet mills, and wholesale lumberyards), urban wood waste (urban wood waste includes wood residues from

MSW (wood chips and pallets), utility tree trimming and/or private tree companies, and construction and demolition sites), and dedicated energy crops (corn, wheat, soybeans, cotton, sorghum, barley, oats, rice, rye, canola, dry edible beans, dry edible peas, peanuts, potatoes, safflower, sunflower, sugarcane, and flaxseed). Intersecting these shapefiles with congressional districts I construct biomass by congressional district geographies dn which I then use to compute an estimate of total biomass, bio_n. Consequently, bio_d is given by:

$$bio_d = \frac{\sum_n \left(\frac{bio_n area_{dn}}{area_d}\right)}{\sum_{d=1}^{D} \sum_n \left(\frac{bio_n area_{dn}}{area_d}\right)}, \tag{A.1.21}$$

where: $area_{dn}$ is the area of biomass by congressional district geography dn, and $area_d$ is the area of congressional district d. The estimate of biomass potential by congressional district, bio_d, is thus simply the share of total biomass potential in a congressional district to the sum of all total biomass potential in the US.

To compute geothermal potential by congressional district d, geo_d, I use *US NREL 2009 Geothermal* shapefile which provides a qualitative assessment of geothermal potential for the U.S. using the Enhanced Geothermal Systems (EGS) for various geothermal geographies n. EGS is based on the levelized cost of electricity with class 1 being most favorable and class 5 being the least favorable. I intersect this shapefile with my shapefile of congressional districts to construct the area of geothermal by congressional district geography if EGS class is less than or equal to 2, $area_{dn}^{c\leq 2}$. Finally geo_d is given by:

$$geo_d = \frac{\sum_n area_{dn}^{c\leq 2}}{\sum_{d=1}^{D} \sum_n area_{dn}^{c\leq 2}}. \tag{A.1.22}$$

Thus, my estimate of geothermal potential by congressional district, geo_d, is simply the share of area in a congressional district with geothermal class of 2 or lower to the sum of all area in the US with a geothermal class of 2 or lower.

To compute solar potential by congressional district d, sol_d, I use *US NREL 2012 Lower*

48 and Hawaii PV 10km Resolution 1998 to 2009 shapefile which provides monthly average and annual average daily total solar resources averaged over surface cells of 0.1 degrees in both latitude and longitude, or about 10 km in size. I intersect this shapefile of 10km grid squares denoted by subscript n with my congressional district shapefile. sol_d is given by:

$$sol_d = \frac{\sum_n \left(\frac{sol_n area_{dn}}{area_d}\right)}{\sum_{d=1}^{D} \sum_n \left(\frac{sol_n area_{dn}}{area_d}\right)}, \tag{A.1.23}$$

where: sol_n is the annual average latitude equals tilt irradiance (or AALETI) (for a given latitude and geography this is a measure of the average solar exposure of a tilted plane held perpendicularly to the sun's rays over the course of a day, or a measure of the maximum possible exposure to the sun's rays that is possible for a given latitude; this is measured in kWh/m2/day), $area_n dn$ is the area of grid square n by congressional district d, and $area_d$ is the area of congressional district d. The estimate of solar potential by congressional district, sol_d, is thus simply the share of total solar potential in a congressional district to the sum of all total solar potential in the US.

Adaptation Exposure

Adaptation exposure reflects relative exposure of a congressional district to sea level rise. This is simply:

$$\delta_{d,s=11} = \frac{seaexp_d}{\sum_{d=1}^{D} seaexp_d}, \tag{A.1.24}$$

where $seaexp_d$ is a measure of congressional district d's exposure to sea-level rise and equals the approximate length of coastline in congressional district d, $coastline_d$, divided by the average elevation of the congressional district, $elevation_d$.

To compute $elevation_d$ I use the *US GS 2012 National Elevation Dataset* which reports mean elevation for geographies defined as a 1/3 Arc second. I intersect this shapefile with my congressional districts shapefile, resulting in 1/3 Arc second by congressional district geographies denoted by the subscript n. The average elevation of a congressional district d

is thus:

$$elevation_d = \frac{\sum_n (elevation_n area_{dn})}{\sum_n area_{dn}}, \tag{A.1.25}$$

where $elevation_n$ is the mean elevation of geography n and $area_{dn}$ is the area of geography n located in congressional district d.

To compute $coastline_d$ I intersect a 100 meter buffer of the *US 2012 National Atlas Coastline One Million-Scale* shapefile with my shapefile of congressional districts. The sum of the areas of the resulting shoreline by congressional district d geographies is a proxy for the length of coastline for congressional district d.

Worker Exposure

Workers exposure reflects the share of employed workers in a congressional district to total employed workers in the US. This is given by:

$$\delta_{d,s=12} = \frac{workers_d}{\sum_{d=1}^{D} workers_d}, \tag{A.1.26}$$

where $workers_d$ is employed workers in congressional district d, the sum of employed individuals in the civilian labor force plus labor in the armed services taken from the *US Census 2007 American Community Survey*.

Building Exposure

Building rule reflects the exposure of a congressional district to energy inefficient residential housing stock. This exposure assigns permits according to population, weighted by the inverse of the average year in which residential structures were built, which is then normalized so that the sum of all rules equals 1. Formally, building exposure is given by:

$$\delta_{d,s=13} = \frac{building_d}{\sum_{d=1}^{D} building_d}, \tag{A.1.27}$$

where $building_d$ is the share of population in congressional district d weighted by the inverse of the average year in which residential structures were built in d to the same for the nation. This is given by:

$$building_d = \frac{pop_d}{year_d}, \tag{A.1.28}$$

where $year_d$ is the mean year in which residential structures were built in congressional district d, and pop_d is the share of population in congressional district d that is 16 years or older to the total national population that is 16 years or older.

To compute $year_d$ I use *US EIA 2009 Residential Energy Consumption Survey, Public Use Microdata File* (RECS) which includes data from 12,083 households selected at random using a complex multistage, area-probability sample design to represent 113.6 million U.S. households, the US Census Bureau's statistical estimate for all occupied housing units in 2009 derived from the *2007 American Community Survey.* The RECS sample was designed to estimate energy characteristics, consumption, and expenditures for the national stock of occupied housing units and the households that live in them. The geographic unit of observation in the sample is 27 reportable domains, which includes 16 individual states and 11 aggregations of states within similar geographic proximity. Each sampled household has a weight reflecting the number of households it reflects in the RECS reportable domain. I compute the weighted mean by reportable domain of the year in which the household's dwelling unit was built (Question A-6 of the Household Questionnaire, *EIA 457-A*), which is self-reported in the sample. I then assign this mean year built to each congressional district located in a reportable domain, which is $year_d$.

Other Civic Sector Exposure

Other Civic Sector exposure reflects the share of population that is 16 years or older in a congressional district to total US population that is 16 years or older. In effect, this simply splits all remaining permits equally to each district on the basis of a proxy for voting population. Other civic sector exposure is given by:

$$\delta_{d,s=14} = \frac{pop_d}{\sum_{d=1}^{D} pop_d}, \tag{A.1.29}$$

where pop_d is the population in congressional district d that is 16 years or older as taken from the *US Census 2007 American Community Survey.*

A.1.4 Offsets Supply

The US EPA's *ADAGE and IGEM v2.3 Data Annex to HR.2454* model output spreadsheet, sheet "Emissions—IGEM Scn02" provides breakdowns of annual emissions reductions, industry abatement, domestic offsets supplied, international offsets supplied, bank balance, and domestic abatement from CCS, bio-electricity, and non-CO_2e sources. Since ACESA allows borrowing and banking of allowances and the caps become tighter over time, in the early years there is expected to be more total abatement than the annual cap to build the bank. In fact, according to the EPA analysis until 2029 allowances are added to bank after which they are drawn down until the bank is fully depleted by 2050.

As shown in Table A.2 for all caps from 2012-2050, total reductions from industry comprise only 42.2% of all emissions reductions, with the remaining 57.8% provided by offsets and other abatement, which I refer to as *total offset supply. Total offset supply* equals the sum of *international offsets supply* plus *net domestic offset supply*, where net domestic offset supply includes domestic offsets supplied as well as all other domestic abatement from CCS, bio-electricity, and non-CO_2e sources as tracked by the EPA's analysis. International offsets account for 63.8% of total offsets supply after discounting,[4] with net domestic offset supply accounting for the remaining 36.2%. Domestic offsets account for 52.3% of net domestic offset supply with an additional 34.4% coming from CCS, and 7.4% and 5.9% coming from domestic capped bio-electricity abatement and domestic capped non-CO_2e abatement sources, respectively.

[4]Under ACESA, international offsets count as only 0.8 of domestic emissions reductions.

The US EPA's *Non-*CO_2 *and Offset MAC Data Annex to HR.2454* provides supplementary data tables used to to compute the various categories of offsets and abatement discussed above. I select η^I to reflect the total supply elasticity from offsets supplied as a result of international avoided deforestation and afforestation. These are by far the bulk of expected international offsets supplied.

To do this I estimate the international offsets supply curve in (1.4.10) using data on offsets supplied from this channel for a given schedule of carbon prices taken from the 'March 2009 Int'l Forest Carbon Sequestration' data file. The original source of this data is Mendelsohn and Sohngen (2007). Taking the natural log of both sides of the international offsets supply curve provides an estimating equation in terms of abatement quantities and prices:

$$\ln A_k^I = \beta_0^I + \eta^I \ln P_k + \epsilon_k^I, \tag{A.1.30}$$

The resulting OLS regression fits the data very well (adjusted $R^2 = 0.933$), with $\eta^I = 2.19$ and is statistically significant at the 5% level.

Likewise, I select η^H to reflect the total supply elasticity from offsets and abatement supplied from: offsets, bio-electricity abatement, ethanol abatement diesel abatement, domestic afforestation, domestic animal waste (CH_4 and N_2O), domestic other agriculture (CH_4 and N_{20}, domestic forest management, and domestic soil sequestration. I note that this includes basically all of the components included in net domestic supply except CCS.

To do this I estimate the net domestic offsets supply curve in (1.4.10) using data on offsets supplied from this channel for a given schedule of carbon prices taken from the 'March 2009 Domestic, Ag, Forest, and Biomass' data file. The original source of this data is Daigneault and Fawcett (2009). Again, taking the natural log of both sides of the net domestic offsets supply curve provides an estimating equation in terms of abatement quantities and prices:

$$\ln A_k^H = \beta_0^H + \eta^H \ln P_k + \epsilon_k^H, \tag{A.1.31}$$

The resulting OLS regression again fits the data very well (adjusted $R^2 = 0.999$), with $\eta^H = 1.22$ and is statistically significant at the 1% level.

I calibrate the share parameters in (1.4.10), ζ^I and ζ^H, such that total offsets supplied as a share of total emissions reductions reflects the average share under the EPA's analysis for all years, with the breakdown between international and domestic offsets reflecting their average shares. To be precise, total emissions reductions of 1,132.6 Tg CO_2e are required in 2021 and the EPA's IGEM analysis predicts an allowance price of $P = \$0.01675$ per Tg CO_2e in the same year. Thus I assume that $A = 654.6$ $(= 0.578 \times 1,132.6)$. Likewise $A^H = 236.7$ $(= 0.209 \times 1,132.6)$ and $A^I = 522.4$ $(= \frac{A-A^H}{0.8})$. Inverting both curves in (1.4.10), I have:

$$\zeta^I = \frac{P}{(A^I)^{\eta^I}}, \tag{A.1.32}$$

and:

$$\zeta^H = \frac{P}{(A^H)^{\eta^H}}. \tag{A.1.33}$$

With offsets in the model, the last market clearing equation is: $\sum_{d=1}^{D} (\xi_d + N_d(r, P, \xi_d)) - A(P) = \bar{E}_0$. I note that offsets do not effect the private good production problem. Rather, offsets only impact the permit market. Since $\sum_{d=1}^{D} \xi_d = \bar{E}_0$, the implied market clearing for purchased permits is now: $\sum_{d=1}^{D} N_d(r, P, \xi_d) = A$ instead of $\sum_{d=1}^{D} N_d(r, P, \xi_d) = 0$. Thus net demand for purchased permits will reflect positive demand for offsets instead of zero.

When offsets are included in the model the private budget constraint is instead: $x_d = \pi_d + rK_d + P\theta_d A^H$, where θ_d is the share of domestic offsets supplied owned by the district.[5] Likewise, aggregate surplus as reported in (1.4.2) is instead: $U_d = u_d - \hat{\kappa}_d$, where $\hat{\kappa}_d = \kappa_d + \kappa^H$ and $\kappa^H = \theta_d \left(\frac{\eta^H}{1+\eta^H}\right) (\zeta^H)^{-\eta^H} P^{1+\eta^H}$. Intuitively, national aggregate surplus is simply the sum of the total value of the labor endowment ($\sum_{d=1}^{D} \pi_d$), producer surplus from supplying capital ($\sum_{d=1}^{D} (rK_d - \kappa_d)$), and producer surplus from supplying domestic offsets nationally

[5] Note that $\sum_{d=1}^{D} x_d = PA^H + r\sum_{d=1}^{D} K_d + \sum_{d=1}^{D} \pi_d = PA^H + r\sum_{d=1}^{D} K_d + \sum_{d=1}^{D} f_d(y_d^*) - r\sum_{d=1}^{D} y_d^* - P\sum_{d=1}^{D} N^* = \sum_{d=1}^{D} f_d(y_d^*) - 0.8PA^I$, given $\sum_{d=1}^{D} y_d^* = \sum_{d=1}^{D} K_d$ and $\sum_{d=1}^{D} N^* = A$ by market clearing in capital and permit markets, respectively.

$\left(\sum_{d=1}^{D}\left(PA^{H}-\kappa^{H}\right)\right)$, less the sum of external damages from emissions ($e^{0}\sum_{d=1}^{D}\phi_{d}$).

A.2 Analytical Derivations

A.2.1 Theoretical Implications of Legislative Bargaining Model with Imperfect Targeting

Consider a model consisting of one sector, i.e. $S = 1$. Ignore labor in the model and define equation (1.4.3) as $X_d = \gamma y_d$. Assume that districts are identical in every way except with respect to their environmental preferences, that is restrict $\zeta = \zeta_d$, $\rho = \rho_d$, and $\omega = \omega_d$ for all districts $d = 1, ..., D$. Assume that $\gamma \geq \left(\frac{1+\eta}{\eta}\right)$. Given $\omega = \omega_d$, it is also the case that $\alpha = \alpha_d$ for all $d = 1, ..., D$.

For simplicity also assume that ϕ_d is distributed uniformly on the interval $[\phi_L, \phi_H]$, where $\frac{\gamma}{D\alpha(1+\eta)} > \phi_H > \phi_L > 0$.[6] Let district subscripts be sorted such that $\phi_1 > ... > \phi_D$. Given this $\phi_1 = \phi_H$ is the greatest climate believer and $\phi_D = \phi_L$ is the greatest climate skeptic. An important implication of this assumption is that: $U_1\left(\bar{E}_0\right) - U_1^{BAU} < ... < U_D\left(\bar{E}_0\right) - U_D^{BAU}$ for all $\bar{E}_0 \leq E_0^{BAU}$. Effectively, this means that the districts $d = 1, ..., D_M$ will be the cheapest to bring into any electoral coalition.

Note that these assumptions imply that $y = y_d$, $K = K_d$, $\pi = \pi_d = 0$, $\kappa = \kappa_d$ for all districts $d = 1, ..., D$. For simplicity, define the producer surplus from supplying capital as $W = rK - \kappa$. Given the other assumptions, it is the case that $y = K = \left(\frac{\bar{E}_0}{\alpha D}\right)$ (and so choosing y is equivalent to choosing $\bar{E}_0$), and thus $r(y) = \zeta y^{\frac{1}{\eta}}$, $P(y) = \frac{\gamma - \zeta y^{\frac{1}{\eta}}}{\alpha}$, $P(y)\bar{E}_0 = P(y)\alpha D y = \gamma D y - D\zeta y^{\left(\frac{1+\eta}{\eta}\right)}$, and $W(y) = \left(\frac{1}{1+\eta}\right)\zeta y^{\left(\frac{1+\eta}{\eta}\right)}$.

Since any randomly drawn proposer p will wish to maximize the permits they receive

[6] The restriction that $\frac{\gamma}{D\alpha(1+\eta)} > \phi_H$ is for analytical tractability. This emerges from the requirement that the cap selected under indirect targeting, $\bar{E}_0^{IT}$, be greater than the cap that generates the greatest amount of permit revenue, $\bar{E}_0^{RM}$, that is to say, that proposed caps are assumed to lie on the right side of the 'Laffer curve' with respect to permits where a tighter cap always implies more permit revenue. The requirement that $\phi_L > 0$ means climate beliefs cannot be negative, and thus all possible proposers $p = 1, ..., D$ will choose an imperfect cap that results in emissions reductions. Were $\phi_L < 0$ then some proposers may seek to achieve an imperfect cap (a mandate) that is greater than emissions under no policy. In that case the cheapest districts to bring into an electoral coalition will be the $d = D_M + 1, ..., D$ group of skeptics, and given the previous assumption emissions increases are substitutes for green pork.

by minimizing the permits they allocate to others, the proposer will seek to offer sufficient permits to get $D_M - 1$ of this group of believer stalwarts on board and then round out any majority coalition with themselves. To avoid subscript confusion I will assume the proposer p is selected from $D_M, ..., D$, and so p plus all of those districts from $d = 1$ to $d = D_M - 1$ will be the core of my yes voting electoral coalition. I compare the results of my model with imperfect targeting to a model where perfect targeting or permits is possible. In this case, the proposer's problem is similar to (1.4.8), except that the proposer chooses a vector of shares to allocate directly to each district, $\boldsymbol{\theta} = \{\theta_d\}_{d=1}^{D}$, instead of a vector of shares to sectors, $\boldsymbol{\theta} = \{\theta_s\}_{s=1}^{S}$, and the final constraint in (1.4.8) is instead $\sum_{d=1}^{D} \theta_d \leq 1$.

Given these assumptions, I can provide some intuition regarding the mechanics of the model. I note that under imperfect targeting, that the firms in each district all have identical production processes and so exposure is identical for all districts, that is, $\delta = \frac{1}{D}$. Thus, for any share of the cap, θ, (only one since $S = 1$) that determines the total pool of permits $\theta \bar{E}_0$ available, each district will be provided an equal number of the permits generated, that is, $\xi_d = \frac{1}{D} \theta \bar{E}_0$ for all $d = 1, ..., D$. Since aggregate surplus is unbounded in x_d and x_d is linear in the value of permits received, any randomly drawn proposer p will choose $\theta = 1$ since this is when the total value of permits they receive will be maximized, and so $\xi_d = \frac{1}{D} \bar{E}_0$ for all $d = 1, ..., D$, where I omit the superscript p for ease of notation. Note that while ξ_d is identical for all $d = 1, ..., D$ under imperfect targeting, under perfect targeting each permit vector will be unique since $\xi_d = \theta_d \bar{E}_0$.

Implications for the Distribution of Permits and Proposer Power

Imperfect targeting provides a blunt instrument for getting legislators on board to pass a climate policy. While the proposer will always select $\theta = 1$, the share of permits needed to secure the coalition, $\hat{\theta} = \hat{\theta}\left(\bar{E}_0\right)$ will be determined by the aggregate surplus of the $D_M - 1$ yes voter such that: $U_{D_M - 1}\left(\hat{\theta}, \bar{E}_0\right) = U_{D_M - 1}^{BAU}$. For all other yes voting districts $d = 1, ..., D_M - 2$ it must be the case that $U_d\left(\hat{\theta}, \bar{E}_0\right) > U_d^{BAU}$, given my assumptions. Thus imperfect targeting will increase the aggregate surplus of most yes voters above and beyond their aggregate surplus under no policy. In addition, $\frac{D-D_M}{D}$ of permits will be allocated to voters who will vote against the policy. From the perspective of the proposer both overcompensating yes voters and compensating no voters is a waste as it implies fewer permits that the proposer will be able to sequester to their own district.

Excess permits available to the proposer—the pool of permits over and above those necessary to secure a majority coalition—under imperfect targeting can be defined as $\frac{1}{D}\left(1-\hat{\theta}\right)$. In sharp contrast, under perfect targeting the proposer would choose $\hat{\hat{\theta}}_d = 0$ for all no voters, and exactly the number of permits needed to obtain the vote of yes voters, that is $\hat{\hat{\theta}}_d = \hat{\hat{\theta}}_d\left(\bar{E}_0\right)$ will be chosen such that: $U_d\left(\hat{\hat{\theta}}_d, \bar{E}_0\right) = U_d^{BAU}$ for all $d = 1, ..., D_M - 1$.[7] Thus, excess permits under perfect targeting will be defined as $1 - \sum_{d=1}^{D} \hat{\hat{\theta}}_d$, which I note is greater than $\frac{1}{D}\left(1-\hat{\theta}\right)$ for any $\bar{E}_0$.

Imperfect targeting, in addition to forcing the proposer to overcompensate yes voters and compensate no voters, also restricts the ability of the proposer to sequester the pool of excess permits directly to their district. For the $\frac{1}{D}\left(1-\hat{\theta}\right)$ of additional permits that the proposer is able to sequester to their district as a result of having proposer power, imperfect targeting forces them to distribute permits to all other districts equal to $\frac{D-1}{D}\left(1-\hat{\theta}\right)$. In contrast, under perfect targeting all of the $1 - \sum_{d=1}^{D} \hat{\hat{\theta}}_d$ total excess permits are provided solely to the proposer. Since the proposer must obtain aggregate surplus under a climate policy at least equal to its aggregate surplus under no policy, $U_p\left(\bar{E}_0\right) \geq U_p^{BAU}$, the inability to perfectly target excess permits to the proposer limits the parameter space in which a proposer is willing to choose a climate policy that will result in emissions reductions. Thus the inability to target green pork decreases the likelihood of climate policy getting passed.

Implications for the Optimal Cap

So far this analysis has simply considered how permits are allocated conditional on the

[7]Unless of course $U_d\left(0, \bar{E}_0\right) > U_d^{BAU}$. In this case, the legislator will vote yes even when it receives no permits, as may be the case for the strongest believers. For those districts then, $\hat{\hat{\theta}}_d = 0$.

cap level chosen by proposer p, $\bar{E}_0$. So long as $\bar{E}_0$ is fixed, the analysis is similar to the classical legislative bargaining models which assume a fixed budget to be allocated to different legislative districts (Baron and Ferejohn (1989), Volden and Wiseman (2007, 2008)). In my model, however, the cap is itself endogenous reflecting the fact that emissions reductions themselves are jointly determined alongside the total value of free permits or green pork, available for redistribution. Consequently, my models of perfect and imperfect targeting will yield different cap levels, $\bar{E}_0^{DT}$ and $\bar{E}_0^{IT}$, respectively. Given that I have already characterized the minimum number of permits needed to secure yes votes conditional on every possible cap in the preceding paragraphs, the cap that solves:

$$
\begin{aligned}
&\max_{\bar{E}_0^{IT}} && U_p\left(\bar{E}_0^{IT}\right) \\
&\text{subject to:} && U_p\left(\bar{E}_0^{IT}\right) \geq U_p^{BAU}, \\
& && \hat{\theta}\left(\bar{E}_0^{IT}\right) \leq 1.
\end{aligned}
\tag{A.2.1}
$$

will be my solution to the legislative bargaining model with imperfect targeting, and the cap that solves:

$$
\begin{aligned}
&\max_{\bar{E}_0^{DT}} && U_p\left(\bar{E}_0^{DT}\right) \\
&\text{subject to:} && U_p\left(\bar{E}_0^{DT}\right) \geq U_p^{BAU}, \\
& && \sum_{d=1}^{D} \hat{\hat{\theta}}_d\left(\bar{E}_0^{DT}\right) \leq 1.
\end{aligned}
\tag{A.2.2}
$$

will be my solution to the legislative bargaining model under perfect targeting.

The solutions to (A.2.1) and (A.2.2) imply the following proposition:

PROPOSITION 1: *Under perfect targeting, the optimal cap selected by a proposer, $\bar{E}_0^{DT}$, maximizes the aggregate surplus of those districts that form the yes voting coalition. This will reflect a cap that is more stringent then the cap that maximizes national aggregate surplus.*

Under imperfect targeting, the optimal cap selected by a proposer, $\bar{E}_0^{IT}$ will be less stringent (e.g. $\bar{E}_0^{DT} \leq \bar{E}_0^{IT}$) then both the cap selected under perfect targeting as well as the cap that maximizes the aggregate surplus of those that form the yes voting coalition. This may be more or less stringent than the cap that maximizes national aggregate surplus.

The first part flows from the observation that $\theta_d^{DT}\left(\bar{E}_0^{DT}\right)$ is such that $U_d\left(\theta_d^{DT}\left(\bar{E}_0^{DT}\right)\right) = U_d^{BAU}$ for all $d = 1, ..., D_M - 1$, which forces the proposer to internalize the aggregate surplus of all yes voters when determining the optimal cap level $\bar{E}_0^{DT}$ since doing so maximizes the permits that the proposer is able to receive.[8] The second claim follows from the fact that the yes electoral coalition is comprised of climate believers which have stronger preferences for emissions reductions than does the national average of all legislators.[9] The third sentence flows from the observation that imperfect targeting limits the ability of the proposer to sequester green pork to those within the electoral coalition. Consequently, the cap a proposer would select under the imperfect model will be less stringent than the cap they would select under the perfect model. The final part reflects the fact because the imperfect model results in a cap that is less restrictive than that which maximizes the aggregate surplus of the yes electoral coalition, then it is more likely to be closer to the cap that maximizes national aggregate surplus since that cap itself is less stringent than the cap that maximizes the

[8]For this to be true, I require the additional assumption that $\hat{\hat{\theta}}_d\left(\bar{E}_0^{DT}\right) > 0$ for all districts that form the yes voting coalition. Given the restrictions on the parameters assumed here this indeed holds. As such, the only coalition that is possible is a minimum winning coalition of size D_M. If some legislators would have voted for the cap even if they received zero permits, then that legislator's preferences would not be internalized by the proposer, and thus $\bar{E}_0^{DT}$ may not maximize the aggregate surplus of those districts that form the yes voting coalition in that case. Instead, it would only maximize the sum of aggregate surplus for those districts for whom $\hat{\hat{\theta}}_d\left(\bar{E}_0^{DT}\right) > 0$ (in the yes voting electoral coalition). A super-majoritarian or unanimous (i.e. non-minimum winning) coalition is possible only if $\hat{\hat{\theta}}_d\left(\bar{E}_0^{DT}\right) = 0$ for *all* legislators in the electoral coalition (if one were to require positive permits to vote yes, then the proposer would just drop them from the coalition). In such a case the proposer will simply select a cap that maximizes their own aggregate surplus.

[9]This result stands in contrast to those bargaining models that examine a more classical policy space in which a global public good can be provided only by reducing the amount of the pork provided. In those models, coalitions can form around those that value the private good or those that value the public good, depending upon the distribution of the marginal utility of the public good relative to the private good across districts, the total number of districts, and the vote threshold (Volden and Wiseman (2007) and (2008), Christiansen (2013)). In these models, the *ex post* policy (conditional on a particular proposer) may deviate from the aggregate surplus maximizing policy, but whether the *ex ante* policy (averaged across all possible proposers) results in a deviation is much less clear.

aggregate surplus of those in the yes electoral coalition.

While Proposition 1, speaks to the relative cap levels of individual proposers, the next proposition speaks to the average of all proposers' caps:

PROPOSITION 2: *Under perfect targeting, the average of all possible proposers' caps will be more stringent than the cap that maximizes national aggregate surplus, e.g* $\left(\frac{1}{D}\right)\sum_{p=1}^{D}\bar{E}_0^{DT}(p) < \bar{E}_0^{NAS}$. *In contrast, under imperfect targeting the average of all caps will be less stringent when* $\eta > 1$ *and may be more or less stringent when* $\eta \leq 1$. *The average cap under perfect targeting will always be more stringent than the average cap under imperfect targeting.*

The first and third claims follow from Proposition 1. If each proposer's cap under the perfect model is more stringent than the policy that maximizes national aggregate surplus or the imperfect cap, then so too must the average of those caps. The second statement reflects the fact that because the imperfect cap is likely to be less stringent than the perfect cap, then it is more likely to be closer to the policy that maximizes aggregate national surplus. However, unlike the perfect case, the imperfect cap may actually end up being too slack relative to the policy that maximizes aggregate national surplus. To the extent that legislators have beliefs with respect to climate change that are more skeptical than those of scientists, what this in effect means is that perfect targeting of green pork is preferred to imperfect targeting since a more stringent cap is likely to emerge when perfect targeting is permitted. However, to the extent that legislators preferences coincide with those of the general public, imperfect targeting is more likely to result in a cap that is closer to the policy that maximizes national aggregate surplus. The leakage in green pork implied by imperfect targeting in this sense increases the likelihood that the imperfect cap will reflect such a policy.

Proof of Perfect Targeting Results

Define the electoral coalition that includes the legislator as the set $\mathbb{D}_p^* = \{(p,d) : d = 1,...,p-1 \bigvee d = p+1,...,D_M \text{ if } p \in [1, D_M - 1] \text{ or } d = 1,...,D_M - 1 \text{ if } p \in [D_M, D]\}$.

I note that this set includes all of the high ϕ type legislators as well as the proposer which can be anyone. So far I have asserted that the set $\mathbb{D}_p^*$ is the only viable electoral coalition. To understand why this is, suppose, for simplicity but without loss of generality, that $p \in [1, D_M - 1]$, and so the coalition consists of all legislators from $d = 1$ to $d = D_M$. Now consider an alternative coalition, $\mathbb{D}_p^{**}$, whereby the $d = D_M$ legislator is replaced with the $d = D$ legislator. This new legislator receives permits equal in value to: $P(y)\xi_D = \max\{0, W^{BAU} - \phi_D \alpha D y^{BAU} - W(y) + \phi_D \alpha D y\}$, whereas the previous legislator would have received $P(y)\xi_{D_M} = \max\{0, W^{BAU} - \phi_{D_M} \alpha D y^{BAU} - W(y) + \phi_{D_M} \alpha D y\}$. For simplicity, but again without loss of generality, suppose $\xi_D > 0$ and $\xi_{D_M} > 0$ that is the zero is not the solution to the maximand.

The difference in the value of permits received between the new and the replaced legislators is given by: $\varepsilon(y) = P(y)\xi_D - P(y)\xi_{D_M} = \alpha D \left(y^{BAU} - y\right)(\phi_{D_M} - \phi_D)$. Since $\phi_{D_M} > \phi_D$, by definition, and a binding cap will be such that $y \leq y^{BAU}$, then $\varepsilon(y) \geq 0$ for all possible caps implied by y. Now, note that the value of permits paid to the proposer equals $P(y)\left(\alpha D y - \sum_{d=1}^{D_M - 1} \xi_d(y) - \xi_{D_M}(y)\right)$ under the original coalition $\mathbb{D}_p^*$ and $P(y)\left(\alpha D y - \sum_{d=1}^{D_M - 1} \xi_d(y) - \xi_D(y)\right)$ under the new coalition $\mathbb{D}_p^{**}$. The difference between these two pay-outs for any cap implied by y is simply $-\varepsilon(y)$. Thus, the proposer would forfeit a pay-off equal to $-\varepsilon(y)$ in order to absorb legislator D in the coalition as opposed to legislator D_M. It follows that the proposer, in wishing to maximize their own utility, will never choose a coalition that includes D over D_M, except for the special case whereby $\xi_{D_M} = 0$ and $\xi_D = 0$ and a super-majoritarian (unanimous if in fact D) coalition will emerge.[10] By extension, if I replaced any members or subsets of members included in $\mathbb{D}_p^*$, with other legislators or groups of legislators along $d = D_M + 1, ..., D$, then the same conclusion must inevitably follow.

Consequently, choosing the cap that solves (A.2.2) is equivalent to finding the y that max-

[10] Although I assumed that $\xi_D > 0$ and $\xi_{D_M} > 0$ to keep things simple, relaxing this assumption does not change this observation. To understand why note that if $\xi_D = 0$ then so too must ξ_{D_M}. That is, if the more skeptical legislator's vote can be secured without any pay-off, then so too must the believer's vote too, all else equal. If $\xi_{D_M} = 0$ when $\xi_D > 0$ then the same analysis clearly follows.

imizes $U_p^D(y) = D_M W(y) + P(y)\alpha D y - \hat{\phi}_p \alpha D y - \sum_{d \neq p \in \mathbb{D}_p^*} U_d^{BAU}$, where $\hat{\phi}_p = \sum_{d \in \mathbb{D}_p^*} \phi_d$, and after substituting in the $\xi_d(y, U_d^{BAU})$ that solves $U_d(y, \xi_d) = U_d^{BAU}$ for all $d \neq p \in \mathbb{D}_p^*$.[11] This yields the cap under perfect targeting equal to: $\bar{E}_0^{DT} = \alpha D \zeta^{-\eta} \left[\left(\gamma - \alpha \hat{\phi}_p \right) \left(\frac{D\eta}{D(1+\eta) - D_M} \right) \right]^{\eta}$.

I note that I can define the aggregate surplus of those in the electoral coalition as $\sum_{d \in \mathbb{D}_p^*} U_d(y)$. Maximizing this object yields the same result as maximizing $U_p^{DT}(y)$ following (A.2.2), since $U_p^{DT}(y) = \sum_{d \in \mathbb{D}_p^*} U_d(y) - \sum_{d \neq p \in \mathbb{D}_p^*} U_d^{BAU}$, and $\sum_{d \neq p \in \mathbb{D}_p^*} U_d^{BAU}$ is exogenous. Consequently, the cap that maximizes $\sum_{d \in \mathbb{D}_p^*} U_d(y)$ is exactly equal to the cap under perfect targeting of $\bar{E}_0^{DT}$. This proves the first sentence in Proposition 1, although this only holds when the optimal coalition is a minimum-winning coalition consisting of $\mathbb{D}_p^*$ where $\xi_d > 0$ for all non-proposers in $\mathbb{D}_p^*$.[12]

Before I showed that of all possible minimum winning coalitions (coalitions that just achieve the vote threshold of D_M legislators) that $\mathbb{D}_p^*$ must be the only optimal solution. However, I did not show that a non-minimum winning coalition, i.e. a super-majoritarian or unanimous coalition is not feasible in this case. I note that in order for a non-minimum winning coalition (a coalition containing more than D_M legislators) to be sustained that $\xi_d = 0$ at least for all non-proposers in $\mathbb{D}_p^*$. Other legislators not included in $\mathbb{D}_p^*$ (i.e. for those $d \in [D_M + 1, D]$) would also need to have $\xi_d = 0$ in order to be included in a super-majoritarian or unanimous coalition. In fact, a super-majoritarian coalition implies that at least some non-proposing legislator would need $\xi_d > 0$ in order to secure their vote (but more than D_M need $\xi_d = 0$), whereas a unanimous coalition is sustained only if all non-proposing legislators require $\xi_d = 0$. Consequently, $\mathbb{D}_p^*$ is the only possible electoral coalition if and only if $\xi_d > 0$ for all legislators in $\mathbb{D}_p^*$ for any possible cap such that $\bar{E}_0^{DT} \leq E_0^{BAU}$. Given the way preferences are ordered and the symmetry assumptions then all legislators $d \in [D_M + 1, D]$

[11] To be precise, this is for the special case of $\mathbb{D}_p^*$ whereby $\xi_d(y) > 0$ for all non-proposing legislators in $\mathbb{D}_p^*$. Similar results can be shown when $\xi_d(y) = 0$ for some non-proposing legislators in the minimum winning coalition.

[12] If $\xi_d = 0$ for some, but not all non-proposing legislators in $\mathbb{D}_p^*$, then the proposer selects a cap that only reflects the preferences of those for whom $\xi_d > 0$. In that case, the perfect cap only maximizes the aggregate surplus of those legislators in $\mathbb{D}_p^*$ for whom $\xi_d > 0$, which is sufficient for this sentence to not be true in some cases.

would also require positive permits in order to bring them into the coalition.

To show that $\xi_d > 0$ for all non-proposers in $\mathbb{D}_p^*$, note that: $P(y^{DT})\xi_d = \left(U_d^{BAU} + \alpha D\phi_d y^{DT} - W(y^{DT})\right)$. Since $P(y^{DT}) > 0$, then to show $\xi_d > 0$ is the same as showing that $\left(U_d^{BAU} + \alpha D\phi_d y^{DT} - W(y^{DT})\right) > 0$. Now $U_d^{BAU} = y^{BAU}\left(\frac{\gamma}{1+\eta} - \alpha D\phi_d\right)$, $\alpha D\phi_d y^{DT} - W(y^{DT}) = y^{DT}\left[\left(\frac{r^{DT}}{1+\eta}\right) - \alpha D\phi_d\right]$, where $r^{DT} = \zeta\left(y^{DT}\right)^{\left(\frac{1}{\eta}\right)}$. I note that $r^{BAU} = \gamma$ and, since $\bar{E}_0^{DT} \leq E_0^{BAU}$ (and thus $y^{DT} \leq y^{BAU}$), then $r^{DT} < \gamma$. Re-arranging terms of $\left(U_d^{BAU} + \alpha D\phi_d y^{DT} - W(y^{DT})\right) > 0$, I have: $\left[y^{BAU}\left(\frac{\gamma}{1+\eta}\right) - y^{DT}\left(\frac{r^{DT}}{1+\eta}\right)\right] + \alpha D\phi_d\left(y^{BAU} - y^{DT}\right) > 0$. Now the second term is positive given that $y^{DT} \leq y^{BAU}$, whereas the first term is positive because $y^{DT} \leq y^{BAU}$ and $r^{DT} < \gamma$. I note that I have shown this for any cap so long as $\bar{E}_0^{DT} \leq E_0^{BAU}$. This is the case here since all legislators are believers by construction, and since a cap larger than E_0^{BAU} can only be achieved through subsidization, that is $P < 0$. Consequently, the minimum winning coalition given by $\mathbb{D}_p^*$ is the only possible coalition.

To show the second sentence in Proposition 1, note that total national aggregate surplus is given by $\sum_{d=1}^{D} U_d(y)$. Maximizing this expression yields a cap that equals: $\bar{E}_0^{NAS} = \alpha D\zeta^{-\eta}\left(\gamma - \alpha\hat{\phi}\right)^{\eta}$, where $\hat{\phi} = \sum_{d=1}^{D}\phi_d$. The second sentence requires us to show that: $\bar{E}_0^{D} \leq \bar{E}_0^{NAS}$, or more simply that: $\left(\gamma - \alpha\hat{\phi}_p\right)\left(\frac{D\eta}{D(1+\eta)-D_M}\right) \leq \left(\gamma - \alpha\hat{\phi}\right)$. Cross-multiplying and re-arranging terms provides: $\gamma \geq \alpha\left[\left(\frac{D\eta - D_N}{D_N}\right)\hat{\phi} - \left(\frac{D\eta}{D_N}\right)\hat{\phi}_d\right]$. For sake of contradiction, suppose instead that $\alpha[\cdot] < \gamma$. Note my earlier requirement that $\frac{\gamma}{D\alpha(1+\eta)} > \phi_H$ and the fact that $\phi_H \geq \phi_d$ for all districts implies that: $\alpha\left[\left(\frac{D\eta - D_N}{D_N}\right)\hat{\phi} - \left(\frac{D\eta}{D_N}\right)\hat{\phi}_d\right] < \alpha\left[\left(\frac{D\eta - D_N}{D_N}\right)D\frac{\gamma}{D\alpha(1+\eta)} - \left(\frac{D\eta}{D_N}\right)D_M\frac{\gamma}{D\alpha(1+\eta)}\right]$, which simplifies down to: $\alpha\left[\left(\frac{D\eta - D_N}{D_N}\right)\hat{\phi} - \left(\frac{D\eta}{D_N}\right)\hat{\phi}_d\right] > \gamma$, which is a contradiction and so the cap that maximizes national aggregate surplus is less stringent then the cap from perfect targeting.

This makes intuitive sense as the cap that maximizes national aggregate surplus reflects an average of the preferences of all districts, whereas the cap from perfect targeting reflects the average of the preferences of all districts included in the coalition $\mathbb{D}_p^*$, which is comprised of districts that are on average greater climate believers than the national average. The first sentence of Proposition 2 follows from this result and Jensen's inequality.

Proof of Imperfect Targeting Results

Without loss of generality, consider a proposer is selected such that $p \in [1, D_M - 1]$. The cap that solves (A.2.1) is equivalent, given my assumptions here, to the y that maximizes:

$$\begin{bmatrix} \max_y W(y) + \frac{1}{D}P(y)\alpha Dy - \phi_p \alpha Dy \\ \textit{subject to:} \\ W(y) + \frac{1}{D}P(y)\alpha Dy - \phi_{D_M}\alpha Dy \geq U_{D_M}^{BAU} \\ W(y) + \frac{1}{D}P(y)\alpha Dy - \phi_p \alpha Dy \geq U_p^{BAU} \end{bmatrix}, \tag{A.2.3}$$

where I note the first constraint in (A.2.3) binds the last voter joining the coalition which again consists of all legislators in the set $\mathbb{D}_p^*$. If the D_M voter is on board, then all of the other $d = 1, ..., D_M - 2$ voters in $\mathbb{D}_p^*$ must also be on board given my symmetry assumptions, the fact that permits are now symmetrically distributed, and the way the ϕ_d's are ordered. If instead the proposer is selected such that $p \in [D_M, D]$, then the first constraint in (A.2.3) is instead replaced by $W(y) + \frac{1}{D}P(y)\alpha Dy - \phi_{D_M - 1}\alpha Dy \geq U_{D_M - 1}^{BAU}$.

In either case, the solution to (A.2.3) consists of two candidates. The first candidate is the unconstrained solution to (A.2.3). In this case only the proposer's preferences matter in determining the cap and, as such, $\bar{E}_0^{ITU} = \alpha D \zeta^{-\eta} (\gamma - \alpha D \phi_p)^\eta$. This is a potential solution for $p \in [1, D]$ so long as the D_M legislator is on board, that is $U_{D_M}(\bar{E}_0^{ITU}) \geq U_{D_M}^{BAU}$. I note that when $p \in [D_M, D]$ that the D_M legislator must be on board since $U_{D_M}(\bar{E}_0^{ITU}) > U_{D_M}^{BAU}$. I note that $\bar{E}_0^{ITU}$ is a possible solution so long as the proposer's aggregate surplus constraint (the second constraint in (A.2.3)) is satisfied. I note that since $\gamma \geq \left(\frac{1+\eta}{\eta}\right)$ and my earlier assumption that $\phi_d \leq \frac{\gamma}{D\alpha(1+\eta)}$ for all $d = 1, ..., D$, it will be the case that $U_p^{ITU} \geq U_p^{BAU}$ for any unconstrained imperfect cap.[13]

The second candidate is the constrained solution, where $\bar{E}_0^{IUC}$ is the analytically in-

[13]Note that $U_p^{ITU} = \zeta^{-\eta}\left(\frac{1}{1+\eta}\right)(\gamma - \alpha D\phi_p)^{(1+\eta)}$, whereas $U_p^{BAU} = \gamma^\eta \zeta^{-\eta}\left(\frac{1}{1+\eta}\right)(\gamma - \alpha D \phi_p)$.

tractable solution that solves: $U_{D_M}(\bar{E}_0^{ITC}) = U_{D_M}^{BAU}$. By the same intuition as before, it must be the case that this is only a candidate solution when $p \in [1, D_M]$, since $U_p(\bar{E}_0^{ITC}) < U_p^{BAU}$ when $p \in [D_M+1, D]$ (that is, a skeptical proposer will have less utility under the constrained cap then under business as usual). I note that when $p \in [1, D_M]$, that $\bar{E}_0^{ITU} < \bar{E}_0^{ITC}$, since the greater believer p would select a more strict cap than that which just satisfied legislator D_M when not constrained. Thus, to prove the third result in Proposition 1, I simply need to show that $\bar{E}_0^{ITU} \geq \bar{E}_0^{DT}$. This is equivalent to showing that $(\gamma - \alpha D\phi_p) \geq \left(\gamma - \alpha\hat{\phi}_p\right)\left(\frac{D\eta}{D(1+\eta)-D_M}\right)$. Cross-multiplication and re-arranging of terms yields: $D_N\gamma \geq \alpha D\left[(D\eta + D_N)\,\phi_p - \eta\hat{\phi}_p\right]$. For sake of contradiction, suppose the opposite inequality holds. Recall again the assumption that $\phi_d \leq \frac{\gamma}{D\alpha(1+\eta)}$ for all $d = 1, ..., D$. Given this the RHS of the previous expression implies that $\alpha D\left[(D\eta + D_N)\,\phi_p - \eta\hat{\phi}_p\right] < D_N\gamma$, which is a contradiction and so the cap selected by imperfect targeting is less stringent then the cap selected through perfect targeting.

Finally, the last line of Proposition 1 follows from the observation that the unconstrained imperfect cap may be larger (if $p \in [D_M + 1, D]$) or smaller (if $p \in [1, D_M - 1]$) than $\bar{E}_0^{NAS}$. The last line of Proposition 2 follows from this observation and Jensen's inequality.

A.3 Numerical Algorithms

A.3.1 To Solve Business as Usual (Competitive) Equilibrium

The solution to the business as usual, or competitive equilibrium is simply the solution to the economic model in the absence of any climate policy:

1. Given the price of capital, r^i, compute the amount of capital demanded and supplied and the amount of capital demanded and construct the excess demand function, $\sum_{d=1}^{436}(K_d - y_d) = 0$.

The result is the solution, r^{BAU}, which can be fed through to provide the full output for this model, $\mathbf{X}^{BAU}\left(r^{BAU}\right)$.

A.3.2 To Solve Legislative Bargaining With Perfect Targeting

Given the cap $\bar{E}_0^i$, other exogenous parameters, and the output from the business as usual run (competitive equilibrium):

1. Given $\bar{E}_0^i$, solve for equilibrium prices that close the economic model $\left(r^i\left(\bar{E}_0^i\right), P^i\left(\bar{E}_0^i\right)\right)$ given (1.4.1).
2. Given $\left(r^i\left(\bar{E}_0^i\right), P^i\left(\bar{E}_0^i\right)\right)$, obtain the aggregate surplus for all legislators excluding the value of permits, $\hat{U}_d^{PT}\left(\bar{E}_0^i\right)$.
3. Given $\hat{U}_d^{PT}\left(\bar{E}_0^i\right)$, $P^i\left(\bar{E}_0^i\right)$, and U_d^{BAU}, compute the level of permits that would be needed to secure any legislator's votes, as $\hat{\xi}_d\left(\bar{E}_0^i\right) = \max\left\{0, \left(\frac{1}{P^i\left(\bar{E}_0^i\right)}\right)\left(U_d^{BAU} - \hat{U}_d^{PT}\left(\bar{E}_0^i\right)\right)\right\}$.
4. Drop the proposer, and sort the remaining $D-1$ vector $\hat{\boldsymbol{\xi}}\left(\bar{E}_0^i\right)$ from lowest to highest.
5. Locate the last zero element, z, of $\hat{\boldsymbol{\xi}}\left(\bar{E}_0^i\right)$. If $z \geq D_M$ then no permits are parsed out to non-proposers and all non-proposers up to and including z are yes voters who will vote for the policy. This allows for the possibility of super-majoritarian or unanimous coalitions, for example if $D > z > D_M$ or $z = D$, respectively. If $z < D_M$, then only a minimum winning coalition is possible, and the first D_M elements of $\hat{\boldsymbol{\xi}}\left(\bar{E}_0^i\right)$ are the positive pay-offs for non-proposers that are placed into $\boldsymbol{\xi}\left(\bar{E}_0^i\right)$, with all other non-proposer elements of $\boldsymbol{\xi}\left(\bar{E}_0^i\right)$ set equal to zero. The indices of those in the coalition are placed into the set $\mathbb{D}_p^i\left(\bar{E}_0^i\right)$.
6. Given $\bar{E}_0^i$ and $\boldsymbol{\xi}\left(\bar{E}_0^i\right)$, compute the residual permits going to the proposer as: $\xi_d\left(\bar{E}_0^i\right) = \bar{E}_0^i - \sum_{d\in\mathbb{D}_p^i\left(\bar{E}_0^i\right)} \xi_d\left(\bar{E}_0^i\right)$. This is then reincorporated into the full vector of permits $\boldsymbol{\xi}\left(\bar{E}_0^i\right)$.
7. Once $\boldsymbol{\xi}\left(\bar{E}_0^i\right)$ has been fully identified, I can evaluate the objective function (e.g. the proposer's aggregate surplus, $U_p^i\left(\bar{E}_0^i\right)$) and evaluate the proposer's aggregate surplus constraint, $U_p^i\left(\bar{E}_0^i\right) \geq U_p^{BAU}$.

The result is the solution, $\bar{E}_0^{PT}$, which can be fed through to provide the full output for this model, $\mathbf{X}^{PT}\left(\bar{E}_0^{PT}\right)$. Given the properties of the other functions of the model, this search is monotonic in $\bar{E}_0^i$, and thus this algorithm should converge quickly to a unique solution. This is a novel algorithm that exploits the logic of the legislative bargaining model to identify $\boldsymbol{\xi}\left(\bar{E}_0^i\right)$ rather than search for $\bar{E}_0^i$ and the entire vector of permits $\boldsymbol{\xi}$, simultaneously.

For a toy version of the model where $D = 10$, I have compared the results from this algorithm to a combinatorial bi-level program that explicitly solves the legislative bargaining model with direct targeting and that follows below. I show in Section A.3.5 using the model of Volden and Wiseman (2007, 2008), that specifying the legislative bargaining model as a nested optimization algorithm results in a solution that exactly replicates the corrected solution of Volden and Wiseman (2008). Although my model is different than Volden and Wiseman (2007, 2008) in that my economic equilibrium is endogenous, the same fundamental legislative bargaining structure applies here. Consequently, this algorithm can be used to solve other legislative bargaining models in which the optimal policy is conditional on the economic equilibrium.

In the context of my model, for the bottom program I first solve, given a possible coalition, $\mathbb{D}_p^k$:

$$\begin{bmatrix} \max_{\bar{E}_0,\boldsymbol{\xi}} U_p\left(\bar{E}_0,\boldsymbol{\xi}\right) \\ \textit{subject to:} \\ U_d\left(\bar{E}_0,\boldsymbol{\xi}\right) \geq U_d^{BAU}\ \forall\, d \in \mathbb{D}_p^k \\ U_p\left(\bar{E}_0,\boldsymbol{\xi}\right) \geq U_p^{BAU} \\ \sum_{d=1}^{D} \xi_d \leq \bar{E}_0 \end{bmatrix}. \tag{A.3.1}$$

Once the optimal policy for every possible coalition has been identified, $\bar{E}_0\left(\mathbb{D}_p^k\right), \boldsymbol{\xi}\left(\mathbb{D}_p^k\right)$, in the upper program the proposer selects the policy *and coalition* that maximizes their aggregate surplus:

$$\begin{bmatrix} \max_{\mathbb{D}_p^k \forall k} U_p\left(\bar{E}_0\left(\mathbb{D}_p^k\right), \boldsymbol{\xi}\left(\mathbb{D}_p^k\right)\right) \\ \textit{subject to:} \\ U_p\left(\bar{E}_0\left(\mathbb{D}_p^k\right), \boldsymbol{\xi}\left(\mathbb{D}_p^k\right)\right) \geq U_p^{BAU} \end{bmatrix}. \tag{A.3.2}$$

I note that solution to (A.3.2) given (A.3.1) is robustly identical to the one returned from my efficient algorithm detailed above.

Finally, I note that my efficient perfect targeting algorithm is similar to the algorithm used to solve the legislative bargaining model with an equal share rule, except that under an equal share rule, $\xi_d = \frac{1}{D}$ and the steps 2-6 are unnecessary.

A.3.3 To Solve Legislative Bargaining With Imperfect Targeting

Given the policy vector $\boldsymbol{\Omega}^i = \left(\bar{E}_0^i, \theta_{s=1}^i, ..., \theta_{s=13}^i\right)$,[14] other exogenous parameters, and the output from the business as usual run (competitive equilibrium):

1. Given $\bar{E}_0^i$ solve for equilibrium prices that close the economic model $\left(r^i\left(\boldsymbol{\Omega}^i\right), P^i\left(\boldsymbol{\Omega}^i\right)\right)$ given (1.4.1).
2. Given $\left(r^i\left(\boldsymbol{\Omega}^i\right), P^i\left(\boldsymbol{\Omega}^i\right), \theta_{s=1}^i, ..., \theta_{s=13}^i\right)$, compute the vector $\xi^i\left(\boldsymbol{\Omega}^i\right)$.
3. Given $\left(r^i\left(\boldsymbol{\Omega}^i\right), P^i\left(\boldsymbol{\Omega}^i\right), \bar{E}_0^i, \xi^i\left(\boldsymbol{\Omega}^i\right)\right)$ obtain the remaining economic output of the model, $\mathbf{X}^i\left(\boldsymbol{\Omega}^i\right)$.
4. Given $\mathbf{X}^i\left(\boldsymbol{\Omega}^i\right)$, compute the vote vector, $v_d^i\left(\boldsymbol{\Omega}^i\right) = 1$ if $U_d^i\left(\boldsymbol{\Omega}^i\right) \geq U_d^{BAU}$ and $v_d^i\left(\boldsymbol{\Omega}^i\right) = 0$ otherwise for all $d = 1, ..., 436$ needed to evaluate the vote constraint, e.g. $D_M - \sum_{d=1}^{D} v_d^i\left(\boldsymbol{\Omega}^i\right) \leq 0$.
5. Given $\mathbf{X}^i\left(\boldsymbol{\Omega}^i\right)$, evaluate the objective function (e.g. the proposer's aggregate surplus, $U_p^i\left(\boldsymbol{\Omega}^i\right)$) and evaluate the proposer's aggregate surplus constraint, $U_p^i\left(\boldsymbol{\Omega}^i\right) \geq U_p^{BAU}$.
6. Given $(\theta_{s=1}^i, ..., \theta_{s=13}^i)$, evaluate the theta constraint, e.g. $\sum_{s=1}^{13} \theta_s^i \leq 1$.

[14] Here I have re-sorted the s index such that the other economic sector (originally $s = 7$) is now $s = 14$. Consequently, by assumption $\theta_{s=14}^i = 0$ and so can be dropped from the analysis.

The result is the solution, $\boldsymbol{\Omega}^{IT}$, which can be fed through to provide the full output for this model, $\mathbf{X}^{IT}\left(\boldsymbol{\Omega}^{IT}\right)$. While the algorithm that solves the perfect targeting model is monotonic in its search arguments, this is not case here. To be precise the imperfect targeting algorithm is not well-behaved with respect to $\left(\bar{E}_0^i, \theta_{s=1}^i, ..., \theta_{s=13}^i\right)$. Thus the solution to this algorithm requires multiple random restarts. Since I invert the algorithm to calibrate the vector $\boldsymbol{\phi}^{ACESA}$ given the observed ACESA policy and electoral coalition I am able to uniquely characterize the true optimum as that which returns the ACESA policy and electoral coalition as its prediction. The additional maximand term in $\hat{\xi}_d^{WM} = \max\left\{\xi_d^{WM}, \max\left\{\xi_d^{WM}\right\}_{d\neq p\in\mathbb{D}^{WM}}\right\}$ assures this by effectively making all other coalitions more expensive from the perspective of the proposer.

A.3.4 To Solve State Model

Given the vector of state caps $\bar{\mathbf{E}}^i$, other exogenous parameters, and the output from the business as usual run (competitive equilibrium):

1. Given $\bar{\mathbf{E}}^i$, identify the price of capital and the price of permits, $\left(r^i\left(\bar{\mathbf{E}}^i\right), P^i\left(\bar{\mathbf{E}}^i\right)\right)$, such that capital and permit markets close following (1.4.18).

2. Given $\left(r^i\left(\bar{\mathbf{E}}^i\right), P^i\left(\bar{\mathbf{E}}^i\right)\right)$, obtain the aggregate surplus vector observed for the current vector of state caps, $\mathbf{V}^i\left(\bar{\mathbf{E}}^i\right)$.

3. For every $k = 1, ..., D$, solve:

   (a) Given $\left\{\bar{E}_d^i\right\}_{d\neq k=1}^D$, obtain $y_{d\neq k}^i\left(\left\{\bar{E}_d^i\right\}_{d\neq k=1}^D\right) = \sum_{d\neq k=1}^D \frac{\bar{E}_d^i}{\alpha_d}$.

   (b) Given $y_{d\neq k}^i\left(\left\{\bar{E}_d^i\right\}_{d\neq k=1}^D\right)$, search for the $\hat{r}^i\left(\left\{\bar{E}_d^i\right\}_{d\neq k=1}^D\right)$ that solves for the conditional competitive equilibrium, e.g. that solves: $\sum_{d=1}^D K_d\left(\hat{r}^i\left(\left\{\bar{E}_d^i\right\}_{d\neq k=1}^D\right)\right) = y_{d\neq k}^i\left(\left\{\bar{E}_d^i\right\}_{d\neq k=1}^D\right) + y_k^i\left(\hat{r}^i\left(\left\{\bar{E}_d^i\right\}_{d\neq k=1}^D\right)\right)$. Note that $y_k^i\left(\cdot\right)$ is simply the no policy solution to (1.4.6) given $\hat{r}^i\left(\cdot\right)$.

   (c) Given $\hat{r}^i\left(\left\{\bar{E}_d^i\right\}_{d\neq k=1}^D\right)$, obtain the conditional competitive equilibrium emissions level for the kth state, $\hat{E}_k\left(\left\{\bar{E}_d^i\right\}_{d\neq k=1}^D\right) = \alpha_k y_k^i\left(\hat{r}^i\left(\left\{\bar{E}_d^i\right\}_{d\neq k=1}^D\right)\right)$ as well as the conditional competitive equilibrium aggregate surplus for the kth state, $\hat{V}_k\left(\left\{\bar{E}_d^i\right\}_{d\neq k=1}^D\right)$.

(d) If $V^i\left(\bar{\mathbf{E}}^i\right) \geq \hat{V}_k\left(\left\{\bar{E}_d^i\right\}_{d\neq k=1}^D\right)$, then:

i. Perturb $\bar{E}_k^i$ by a small increment, $\varepsilon > 0$, call this $\bar{E}_{k2}^i\left(\bar{E}_k^i\right) = (1+\varepsilon)\bar{E}_k^i$.

ii. Given $\bar{E}_{k2}^i\left(\bar{E}_k^i\right)$ and holding $\left\{\bar{E}_d^i\right\}_{d\neq k=1}^D$ fixed, re-solve for the market prices $\left(r_2^i\left(\bar{E}_k^i, \left\{\bar{E}_d^i\right\}_{d\neq k=1}^D\right), P_2^i\left(\bar{E}_k^i, \left\{\bar{E}_d^i\right\}_{d\neq k=1}^D\right)\right)$ that satisfy market clearing.

iii. Given $\left(r_2^i\left(\bar{E}_k^i, \left\{\bar{E}_d^i\right\}_{d\neq k=1}^D\right), P_2^i\left(\bar{E}_k^i, \left\{\bar{E}_d^i\right\}_{d\neq k=1}^D\right)\right)$, compute the new aggregate surplus, $V_{k2}^i\left(\bar{E}_k^i, \left\{\bar{E}_d^i\right\}_{d\neq k=1}^D\right)$.

iv. Given $V_k^i\left(\bar{E}_k^i, \left\{\bar{E}_d^i\right\}_{d\neq k=1}^D\right)$ and $V_{k2}^i\left(\bar{E}_{k2}^i, \left\{\bar{E}_d^i\right\}_{d\neq k=1}^D\right)$ characterize the kth equation in the system to set equal to zero as: $\frac{dV_k}{d\bar{E}_k} = \left(\frac{V_{k2}^i\left(\bar{E}_k^i, \left\{\bar{E}_d^i\right\}_{d\neq k=1}^D\right) - V_k^i\left(\bar{E}_k^i, \left\{\bar{E}_d^i\right\}_{d\neq k=1}^D\right)}{\bar{E}_{k2}^i\left(\bar{E}_k^i\right) - \bar{E}_k^i}\right)$. Note that this is a numerical approximation of the first-order condition to the state's optimization problem given by (1.4.14), which is conditional on all other state policies $\left\{\bar{E}_d^i\right\}_{d\neq k=1}^D$ and evaluated at $\bar{E}_k^i$. Because I only enter here if the above inequality is satisfied this is the non-binding solution to (1.4.14).

(e) Else, characterize the kth equation in the system to set equal to zero as: $\hat{E}_k\left(\left\{\bar{E}_d^i\right\}_{d\neq k=1}^D\right) - \bar{E}_k^i$. That is to say, if a state policymaker does not wish to set a cap, then they will emit at the conditional competitive equilibrium which is also conditional on all other state policies $\left\{\bar{E}_d^i\right\}_{d\neq k=1}^D$. Thus, this is the binding solution to (1.4.14).

The solution that sets the resulting 50 by one system of equations equal to zero is, $\bar{\mathbf{E}}^{SP}$, which can be fed through to provide the full output for this model, $\mathbf{X}^{SP}\left(\bar{\mathbf{E}}^{SP}\right)$.

A.3.5 Comparison of Algorithmic Solution of Nested Optimization Problem to Analytic Solution Under the Basic V&W Model

Recall the set-up from Volden and Wiseman (2007, 2008) for the simplest model of homogeneous jurisdictions. Let there be n jurisdictions, infinite time periods with discounting between time periods at discount rate $\delta \in [0,1]$. There is a global public good y and as well as local public goods $x_k \forall k = 1, ..., n$. The central government plays a game of 'split the dollar' between the two classes of goods, e.g. the central government has a budget constraint given by: $y + \sum_{k=1}^{n} x_k = 1$. The preferences of each jurisdiction's legislator are given by: $U_k = \alpha x_k + y$. Note that α reflects the marginal rate of substitution between the local good x_k and the global good y.

Analytic Solution to the Basic V&W Model

Let z denote the randomly selected proposer in a given period. Effectively there are three types of solutions that emerge: 1.) Collective, e.g. $y = 1$ and $x_k = 0 \forall k = 1, ..., n$ and whereby the vote is unanimous, 2.) Mixed, e.g. $x_z = \frac{n(1-\delta)}{n(1-\delta)+\delta\alpha} > 0$, $y = 1 - x_z = \frac{\delta\alpha}{n(1-\delta)+\delta\alpha} > 0$ and $x_{\neg z} = 0$ and whereby the vote is unanimous, and 3.) Particularistic, e.g. $y = 0$, $x_z = 1 - \left(\frac{\delta(n-1)}{2n}\right) > 0$ and $x_{\neg z} = \left(\frac{\delta}{n}\right) > 0$ for those in a minimum winning coalition and $x_{\neg z} = 0$ for those not in the MWC. Note that these three coalitions imply two cut-off's, $\alpha_{CM} = 1$ and $\alpha_{MP} = \frac{n+1}{2}$. The collective solution results for $\alpha \in (0, \alpha_{CM}]$, the mixed solution for $\alpha \in (\alpha_{CM}, \alpha_{MP}]$, and the particularistic solution for $\alpha \in (\alpha_{MP}, \infty)$.

Solving the Basic V&W Model as a Nested Optimization Problem

Here I formulate the Volden and Wiseman (2007, 2008) problem for the case of homogeneous jurisdictions as a nested optimization problem. My objective is two-fold. First, I wish to show that if I set up the problem in this way, that I obtain the same solutions as those given in Volden and Wiseman (2007, 2008). Secondly, I wish to show that my algorithmic approach for identifying the vector of continuation utilities converges to the Volden and Wiseman (2007, 2008) solution as the number of iterations approaches infinity.

Before proceeding, define u_s^s as the utility received when s is selected as proposer, u_s^{in} as the utility received when s is not the proposer but is included within the coalition, and u_s^{out} as the utility received when s is not the proposer and outside the coalition. Given the assumption of homogeneity in this example, it will be the case that the proposer utility will be same for any legislator chosen as proposer, or $u^z = u_s^s = u_t^t \, \forall \, s \neq t = 1, ..., n$; the utility received by non-proposers in the electoral coalition will be the same, or $u^{in} = u_s^{in} = u_t^{in} \, \forall \, s \neq t = 1, ..., n$; and the utility received by those outside of the electoral coalition will be the same, or $u^{out} = u_s^{out} = u_t^{out} \, \forall \, s \neq t = 1, ..., n$. Likewise, the continuation utility for all legislators will be the same or $V = V_s = V_t \, \forall \, s \neq t = 1, ..., n$. Finally, I can also strip out the proposer index from my candidate coalitions, that is $\mathbb{J}_k = \mathbb{J}_k(s) = \mathbb{J}_k(t) \, \forall \, s \neq t = 1, ..., n$. Then the upper optimization problem is given by:

$$v_z(\mathbb{J}_k) = \left[\begin{array}{c} \max_{\{x_s\}_{s=1}^n, y} \alpha x_z + y \\ \textit{subject to:} \\ \alpha x_{in} + y \geq \delta V \; \forall s \in \mathbb{J}_k \\ y + \sum_{s=1}^n x_s = 1 \end{array} \right], \tag{A.3.3}$$

where I note that $V = \frac{1}{n}u^z + \frac{n-1}{2n}u^{in} + \frac{n-1}{2n}u^{out}$ in the case of a MWC, $\mathbb{J}_{MWC}$, and $V = \frac{1}{n}u^z + \frac{n-1}{n}u^{in}$ in the case of a unanimous coalition, $\mathbb{J}_{Una}$. Given the earlier definitions, it is the case that $\alpha x_{in} + y = u^{in}$ in the constraints provided in (A.3.3). Likewise, $\alpha x_z + y = u^z$ in the objective function given in (A.3.3).

Finally, the bottom level optimization problems is given by:

$$v_z = \left[\max_k \{ v_z(\mathbb{J}_{Una}), v_z(\mathbb{J}_{Una}) \} \right]. \tag{A.3.4}$$

Given, (A.3.4), it is the case that a unanimous coalition is preferred when $v_z(\mathbb{J}_{Una}) \geq v_z(\mathbb{J}_{Una})$, and a MWC is preferred when the reverse is true. I now proceed by solving (A.3.3) for the two coalition cases.

Solution for the Case of a MWC

Note that the inequality constraints in (A.3.3) are effectively, $u^{in} \geq \delta V$. It follows that I can net out u^{in} in V since it is determined as part of the solution to the proposer's problem.

(While in the case of homogeneous jurisdictions I could simply directly substitute in *all* of the policies being considered into my equation for V, in the case of heterogeneous jurisdictions this is not possible for a large number of types and/or n. Since I net u^{in} out of V when I solve the heterogeneous model, I follow these same steps to demonstrate equivalence here.) For the case of a MWC, this is:

$$\begin{aligned}
&u^{in} \geq \delta V \Leftrightarrow \\
&u^{in} \geq \frac{\delta}{n}u^{z} + \frac{\delta(n-1)}{2n}u^{in} + \frac{\delta(n-1)}{2n}u^{out} \Leftrightarrow \\
&u^{in} \geq \left(\frac{2n\delta}{2n-\delta(n-1)}\right)\left[\left(\frac{1}{n}\right)u^{z} + \left(\frac{n-1}{2n}\right)u^{out}\right] \Leftrightarrow \\
&u^{in} \geq \hat{\delta}\hat{V}, \qquad \text{(A.3.5)}
\end{aligned}$$

where: $\hat{\delta} = \left(\frac{2n\delta}{2n-\delta(n-1)}\right)$ and $\hat{V} = \left[\left(\frac{1}{n}\right)u^{z} + \left(\frac{n-1}{2n}\right)u^{out}\right]$.

In the case of a MWC (A.3.3), given (A.3.5), implies:

$$v_z\left(\mathbb{J}_{MWC}\right) = \begin{bmatrix} \max_{x_z, x_{in}, y} \alpha x_z + y \\ \textit{subject to:} \\ \alpha x_z + y \geq \hat{\delta}\hat{V} \ \left(\mu_z\right) \\ \alpha x_{in} + y \geq \hat{\delta}\hat{V} \ \left(\mu_{in}\right) \text{ for } \frac{n-1}{2} \text{ legislators} \\ y + \left(\frac{n-1}{2}\right)x_{in} + x_z = 1 \ \left(\lambda\right) \end{bmatrix}. \qquad \text{(A.3.6)}$$

(A.3.6) yields the following first-order conditions:

$$\begin{aligned}
\frac{\partial L}{\partial x_z} &\equiv \alpha\left(1+\mu_z\right) \leq \lambda, \text{ ``='' if } x_z > 0, \\
\frac{\partial L}{\partial x_{in}} &\equiv \alpha\mu_{in} \leq \left(\frac{n-1}{2}\right)\lambda, \text{ ``='' if } x_{in} > 0, \\
\frac{\partial L}{\partial y} &\equiv 1+\mu_z+\mu_{in} \leq \lambda, \text{ ``='' if } y > 0, \\
\frac{\partial L}{\partial \mu_z} &\equiv \mu_z \geq 0;\ \mu_z\left(x_z + y - \hat{\delta}\hat{V}\right) = 0;\ \alpha x_z + y \geq \hat{\delta}\hat{V}, \\
\frac{\partial L}{\partial \mu_{in}} &\equiv \mu_{in} \geq 0;\ \mu_{in}\left(x_{in} + y - \hat{\delta}\hat{V}\right) = 0;\ \alpha x_{in} + y \geq \hat{\delta}\hat{V}.
\end{aligned} \tag{A.3.7}$$

(A.3.7) has eight possible solutions (1. $x_z > 0$, $x_{in} > 0$, $y > 0$; 2. $x_z > 0$, $x_{in} > 0$, $y = 0$; 3. $x_z > 0$, $x_{in} = 0$, $y > 0$; 4. $x_z > 0$, $x_{in} = 0$, $y = 0$; 5. $x_z = 0$, $x_{in} > 0$, $y > 0$; 6. $x_z = 0$, $x_{in} = 0$, $y > 0$; 7. $x_z = 0$, $x_{in} > 0$, $y = 0$; and 8. $x_z = 0$, $x_{in} = 0$, $y = 0$) of which only three do not yield a contradiction (2 or *Particularistic.* $x_z > 0$, $x_{in} > 0$, $y = 0$; 3 or *Mixed.* $x_z > 0$, $x_{in} = 0$, $y > 0$; and 6 or *Collective.* $x_z = 0$, $x_{in} = 0$, $y > 0$). Of these three the Mixed and Collective cases are not MWC, but instead unanimous and so are superseded by the solution that continues below.

The Particularistic solution to (A.3.7) is given by:

$$\begin{aligned}
x_z &= 1 - \left(\frac{n-1}{2\alpha}\right)\hat{\delta}\hat{V} > 0, \\
x_{in} &= \left(\frac{1}{\alpha}\right)\hat{\delta}\hat{V} > 0, \text{ and} \\
y &= 0,
\end{aligned} \tag{A.3.8}$$

which holds for the case when $\alpha > \left(\frac{n+1}{2}\right)$, given the restrictions on the LaGrange multipliers given in (A.3.7).

Algorithmic Convergence to V&W Solution for the Particularistic Case

To continue with my solution, I need to recompute my calculation of $\hat{V}$ for each iteration t given the latest Particularistic solution. Given the current estimate of the continuation utility, $\hat{V}_t$, the new estimate of $\hat{V}$, $\hat{V}_{t+1}$, given that $\hat{V}_{t+1} = \left[\left(\frac{1}{n}\right)(\alpha x_z + y) + \left(\frac{n-1}{2n}\right) y\right]$ after substituting in my solution given in (A.3.8) (which is a function of $\hat{V}_t$) is given by:

$$\hat{V}_{t+1} = \left(\frac{\alpha}{n}\right) - \left(\frac{\delta(n-1)}{2n - \delta(n-1)}\right) \hat{V}_t. \tag{A.3.9}$$

Repeated substitution of (A.3.9) implies:

$$\hat{V}_t = \left(\frac{\alpha}{n}\right) \left[\sum_{s=0}^{t-1} \left(\frac{-\delta(n-1)}{2n - \delta(n-1)}\right)^s\right] + \left(\frac{-\delta(n-1)}{2n - \delta(n-1)}\right)^t \hat{V}_1. \tag{A.3.10}$$

Initializing my continuation utility to be $\hat{V}_1 = 0$, note that the limit as t approaches infinity is given by:

$$\hat{\hat{V}} = \lim_{t\to\infty} \hat{V}_t = \lim_{t\to\infty} \left(\frac{\alpha}{n}\right) \left[\sum_{s=0}^{t-1} \left(\frac{-\delta(n-1)}{2n - \delta(n-1)}\right)^s\right] = \left(\frac{\alpha}{n}\right) \left(\frac{2n - \delta(n-1)}{2n}\right). \tag{A.3.11}$$

Given (A.3.11), I substitute $\hat{\hat{V}}$ into (A.3.8), which is the final solution for the Particularistic case using my approach:

$$\begin{aligned} x_z &= 1 - \left(\frac{n-1}{2}\right)\left(\frac{\delta}{n}\right), \\ x_{in} &= \left(\frac{\delta}{n}\right), \text{ and} \\ y &= 0. \end{aligned} \tag{A.3.12}$$

It is clear that the solution from my approach for the Particularistic case is the same as that given in Volden and Wiseman (2007, 2008). It is also clear that the parameter restriction which characterizes this solution, $\alpha > \left(\frac{n+1}{2}\right) = \alpha_{MP}$, is the same as the corrected value reported in Volden and Wiseman (2008).

Solutions for the Case of a Unanimous Coalition

For the unanimous coalition case, netting out u^{in} in V implies:

$$\begin{aligned}
&u^{in} \geq \delta V \Leftrightarrow \\
&u^{in} \geq \frac{\delta}{n} u^z + \frac{\delta(n-1)}{n} u^{in} \Leftrightarrow \\
&u^{in} \geq \frac{\delta}{(n - \delta(n-1))} u^z \Leftrightarrow \\
&u^{in} \geq \hat{\delta}\hat{V},
\end{aligned} \tag{A.3.13}$$

where: $\hat{\delta} = \frac{\delta}{(n-\delta(n-1))}$ and $\hat{V} = u^z$.

In the case of a unanimous coalition (A.3.3), given (A.3.13) implies:

$$v_z\left(\mathbb{J}_{Una}\right) = \begin{bmatrix} \max_{x_z, x_{in}, y} \alpha x_z + y \\ \textit{subject to:} \\ \alpha x_z + y \geq \hat{\delta}\hat{V} \;\; (\mu_z) \\ \alpha x_{in} + y \geq \hat{\delta}\hat{V} \;\; (\mu_{in}) \text{ for } n-1 \text{ legislators} \\ y + (n-1)\, x_{in} + x_z = 1 \;\; (\lambda) \end{bmatrix}. \tag{A.3.14}$$

(A.3.14) yields the following first-order conditions:

$$\begin{aligned}
\frac{\partial L}{\partial x_z} &\equiv \alpha\left(1+\mu_z\right) \leq \lambda,\ \text{``=''}\text{ if } x_z > 0,\\
\frac{\partial L}{\partial x_{in}} &\equiv \alpha\mu_{in} \leq \left(n-1\right)\lambda,\ \text{``=''}\text{ if } x_{in} > 0,\\
\frac{\partial L}{\partial y} &\equiv 1+\mu_z+\mu_{in} \leq \lambda,\ \text{``=''}\text{ if } y > 0,\\
\frac{\partial L}{\partial \mu_z} &\equiv \mu_z \geq 0;\ \mu_z\left(x_z+y-\hat{\delta}\hat{V}\right)=0;\ \alpha x_z + y \geq \hat{\delta}\hat{V},\\
\frac{\partial L}{\partial \mu_{in}} &\equiv \mu_{in} \geq 0;\ \mu_{in}\left(x_{in}+y-\hat{\delta}\hat{V}\right)=0;\ \alpha x_{in} + y \geq \hat{\delta}\hat{V}.
\end{aligned} \tag{A.3.15}$$

(A.3.14) has eight possible solutions (1. $x_z > 0$, $x_{in} > 0$, $y > 0$; 2. $x_z > 0$, $x_{in} > 0$, $y = 0$; 3. $x_z > 0$, $x_{in} = 0$, $y > 0$; 4. $x_z > 0$, $x_{in} = 0$, $y = 0$; 5. $x_z = 0$, $x_{in} > 0$, $y > 0$; 6. $x_z = 0$, $x_{in} = 0$, $y > 0$; 7. $x_z = 0$, $x_{in} > 0$, $y = 0$; and 8. $x_z = 0$, $x_{in} = 0$, $y = 0$) of which only two do not yield a contradiction (3 or *Mixed.* $x_z > 0$, $x_{in} = 0$, $y > 0$; and 6 or *Collective.* $x_z = 0$, $x_{in} = 0$, $y > 0$).

The Mixed solution to (A.3.15) is given by:

$$\begin{aligned}
x_z &= 1-\hat{\delta}\hat{V} > 0,\\
x_{in} &= 0,\ \text{and}\\
y &= \hat{\delta}\hat{V} > 0,
\end{aligned} \tag{A.3.16}$$

which holds for the case when $\left(\frac{n+1}{2}\right) \geq \alpha > 1$, given the restrictions on the LaGrange multipliers given in (A.3.15).

The Collective solution to (A.3.15) is given by:

$$\begin{aligned} x_z &= 0, \\ x_{in} &= 0, \text{ and} \\ y &= 1, \end{aligned} \tag{A.3.17}$$

which holds for the case when $\alpha \leq 1$, given the restrictions on the LaGrange multipliers given in (A.3.15). Since (A.3.17) is not a function of $\hat{V}$, it will be the case that the algorithm terminates on the first iteration when $\alpha \leq 1$.

Algorithmic Convergence to V&W Solution for the Mixed Case

However, the Mixed solution is a function of $\hat{V}$. As before, to complete my solution, I need to recompute my calculation of $\hat{V}$ for each iteration t given the latest Mixed solution. Given the current estimate of the continuation utility, $\hat{V}_t$, the new estimate of $\hat{V}$, $\hat{V}_{t+1}$, given that $\hat{V}_{t+1} = (\alpha x_z + y)$ after substituting in my solution given in (A.3.8) (which is a function of $\hat{V}_t$) is given by:

$$\hat{V}_{t+1} = \alpha + (1-\alpha)\frac{\delta}{(n - \delta(n-1))}\hat{V}_t. \tag{A.3.18}$$

Repeated substitution of (A.3.18) implies:

$$\hat{V}_t = \alpha\left[\sum_{s=0}^{t-1}\left(\frac{\delta(1-\alpha)}{n-\delta(n-1)}\right)^s\right] + \left(\frac{\delta(1-\alpha)}{n-\delta(n-1)}\right)^t \hat{V}_1. \tag{A.3.19}$$

Initializing my continuation utility to be $\hat{V}_1 = 0$, note that the limit as t approaches infinity is given by:

$$\hat{\hat{V}} = \lim_{t\to\infty}\hat{V}_t = \lim_{t\to\infty}\alpha\left[\sum_{s=0}^{t-1}\left(\frac{\delta(1-\alpha)}{n-\delta(n-1)}\right)^s\right] = \alpha\left(\frac{n-\delta(n-1)}{n(1-\delta)+\alpha\delta}\right). \tag{A.3.20}$$

Given (A.3.20), I substitute $\hat{\hat{V}}$ into (A.3.16), which is the final solution for the Mixed case using my approach:

$$\begin{aligned} x_z &= \left(\frac{n(1-\delta)}{n(1-\delta)+\alpha\delta}\right), \\ x_{in} &= 0, \text{ and} \\ y &= \left(\frac{\alpha\delta}{n(1-\delta)+\alpha\delta}\right). \end{aligned} \tag{A.3.21}$$

It is clear that the solution from my approach for the Mixed case is the same as that given in Volden and Wiseman (2007, 2008). It is also clear that the parameter restriction which characterizes this solution, $\alpha \in (1, \left(\frac{n+1}{2}\right)]$, is the same reported in Volden and Wiseman (2007, 2008).

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A.4 Additional Figures and Tables

Table A.1: Emissions Intensity By Sector

Emissions Intensity (kg CO_2e per \$ value of capital)	0.73
Electricity	13.72
Natural Gas	20.4
Heating Oil)	9.922
Petroleum Refineries	20.03
Automobiles	0.00
Trade Vulnerable Industries	1.36

Notes: Mean reported for congressional districts with standard deviation in parentheses.

Table A.2: Share of Offsets to Total Emissions Reductions Under ACESA

	Average Annual	Totals: 2012-2050	Share of Total Reductions	Share of Total Offsets	Share of Net Domestic Offsets
Emissions Reductions (Tg CO_2e)	2,917.14	113,768.41	100.0%		
From Industry Abatement	1,231.82	48,040.96	42.2%		
From Offsets and Other Abatement	1,685.32	65,727.45	57.8%	100.0%	
International Offsets	1,075.51	41,944.94	36.9%	63.8%	
Net Domestic Offsets	609.81	23,782.47	20.9%	36.2%	100.0%
Domestic Offsets	318.85	12,435.32	10.9%	18.9%	52.3%
CCS	209.95	8,188.09	7.2%	12.5%	34.4%
Domestic Capped Bio-Electric	44.94	1,752.66	1.5%	2.7%	7.4%
Domestic Capped Non-CO_2e Abatement	36.06	1,406.40	1.2%	2.1%	5.9%

Table A.3: Share of Regional Delegation Voting “aye” on Waxman-Markey

Region	Number of Yes Votes	Total Number of Reps	% of Yes Votes by Region
Northeast	74	92	80.43%
West	56	97	57.73%
Midwest	43	92	46.74%
South	31	99	31.31%
Plains	15	55	27.27%

Notes: Regions here are defined according to the ADAGE model documentation.

Appendix B

Appendix to Are there Carbon Savings from US Biofuel Policies? The Critical Importance of Accounting for Leakage in Land and Fuel Markets

This appendix provides the intermediate steps in the derivation of the marginal emissions formula (Section B.1), a full exposition of the simulation model and additional results. In Section B.2 we present the functional forms used in the simulation model and highlight the key differences between the analytic model and the simulation model. Section B.3 discusses the parameter values and data sources used for calibration. Section B.4 outlines the assumptions and data sources which are the basis for our construction of marginal emissions factors. In Section B.5 we outline the assumptions regarding the dynamic trends that underlie our simulation results. Section B.7 validates our baseline against historical data and compares our projections to the USDA's Long Term Projections. Section B.8 presents additional sensitivity analysis not reported in the text. Finally, Section B.9 contains tabular results for the impact of the RFS on crop prices, intended emissions savings and leakage per liter of ethanol added by the RFS.

B.1 Derivation of Marginal Emissions Formula

To derive the marginal emissions formula, equation (2.3.19), we totally differentiate total emissions with respect to the RFS, θ:

$$\begin{aligned}\frac{dGHG}{d\theta} &= \phi_G \frac{dG}{d\theta} + \phi_E \frac{dE}{d\theta} + \phi_Y \frac{dA_Y}{d\theta} + \phi_Z \frac{dA_Z}{d\theta} \\ &\quad + \phi_{N,D} \frac{dA_{N,D}}{d\theta} + \phi_{N,W} \frac{dA_{N,W}}{d\theta} + \phi_R \frac{dR_W}{d\theta}\end{aligned} \tag{B.1.1}$$

where:

$$\frac{dG}{d\theta} = g_F \frac{dF}{d\theta} + F \frac{dg_F}{d\theta} \qquad \text{and} \qquad \frac{dE}{d\theta} = e_F \frac{dF}{d\theta} + F \frac{de_F}{d\theta}. \tag{B.1.2}$$

Adding the following terms to equation (B.1.1)

$$\begin{aligned}&\phi_G \left(\frac{dE}{d\theta} - \frac{dE}{d\theta} \right) \\ &\phi_Y \frac{dE}{d\theta} \left(\tilde{A}_Y - \tilde{A}_Y \right)\end{aligned} \tag{B.1.3}$$

recognizing that

$$\frac{dF}{d\theta} = \frac{dG}{d\theta} + \frac{dE}{d\theta} \tag{B.1.4}$$

and rearranging terms yields equation (2.3.19). The equations in (B.1.3) allow for the intended emissions savings and leakage. Equation (B.1.4) follows from the equations in (B.1.2).

B.2 Functional Forms

We use a numerical model with the same general structure as our analytical model to quantify each of the terms of equation (2.3.19) for the years 2009-2015. Here we lay out the key functional form assumptions of the numerical model.

Consumer

The representative agent is assumed to have preferences given by the following nested constant elasticity of substitution (CES) utility function:

$$\begin{aligned} U(F,X,C,H) &= \left[\alpha_U M(F,H)^{\frac{\sigma_U - 1}{\sigma_U}} + (1-\alpha_U)\, W(C,X)^{\frac{\sigma_U - 1}{\sigma_U}} \right]^{\frac{\sigma_U}{\sigma_U - 1}} \\ W(C,X) &= \gamma_W \left[\alpha_W C^{\frac{\sigma_W - 1}{\sigma_W}} + (1-\alpha_W)\, X^{\frac{\sigma_W - 1}{\sigma_W}} \right]^{\frac{\sigma_W}{\sigma_W - 1}} \\ M(F,H) &= \gamma_M \left[\alpha_M F^{\frac{\sigma_M - 1}{\sigma_M}} + (1-\alpha_M)\, H^{\frac{\sigma_M - 1}{\sigma_M}} \right]^{\frac{\sigma_M}{\sigma_M - 1}} \end{aligned} \tag{B.2.1}$$

where W is a composite of food and other consumption, M denotes vehicle miles traveled (VMT)[1] and H denotes fixed costs of driving. σ_U, σ_W, and σ_M are elasticities of substitution, $\alpha_U, \alpha_W, \alpha_M$ are share parameters, and γ_W and γ_M are scale parameters. Nesting utility in this way implies weak-separability between VMT and other consumption. In embedding the VMT decision we permit substitutability between fixed costs of driving and blended fuel allowing fuel economy to be endogenously determined.[2]

In the simulation model the terms-of-trade balance (value of crop exports sold less crude oil imports purchased) added to the consumers income. Formally, the value of the terms-of-trade balance, T is given by:

$$T = \int_{P_Y^0}^{P_Y^{RFS}} Y_{X,W}(P_Y, P_Z) dP_Y + \int_{P_Z^0}^{P_Z^{RFS}} Z_{X,W}(P_Y, P_Z) dP_Z - \int_{P_R^0}^{P_R^{RFS}} R_W(P_R) dP_R, \quad \text{(B.2.2)}$$

where the prices superscripted 0 are baseline prices and the prices superscripted RFS are prices when the RFS is imposed.

Land Use Allocation

The land owner's decision closely follows equation (2.3.11), except that we consider five crops, corn soybeans, wheat, hay and cotton, as well as land allocated to the CRP.[3] We assume that the yield (payment) functions in (2.3.11) is linear in the quantity of land allocated to each land use (A_i):

$$y_i(A_i) = \beta_i - \delta_i A_i \quad \text{(B.2.3)}$$

where β_i and δ_i are the intercept and exogenous slope coefficients of crop i's linear yield function.

Only corn is used to produce ethanol, while corn, soybeans, hay and wheat are all used in food production. Corn, soybeans, wheat and cotton are exported to the rest of the world.

Fuel Markets

Fuel blenders, equation (2.3.4) in the analytical model, are constrained by a linear production function:

$$F = \Gamma_F E + G \quad \text{(B.2.4)}$$

[1]We use "miles" and "VMT" in the description here because it follows the literature. We report values in kilometers to maintain consistency in metric units throughout the paper.

[2]Our use of a CES functional form to model the trade-off between blended fuel and fixed costs of driving is commonly used by other simulation models in this area, see for example Parry and Small (2005). Importantly, this functional form permits price induced substitution from blended fuel to fixed costs of driving, in effect permitting an improvement in the average fuel economy of the vehicle fleet in response to fuel price changes, which has important implications for domestic fuel market leakage. Critically, this functional form allows one to distinguish the own price elasticity of blended fuel from the elasticity of VMT with respect to the price of blended fuel. As the econometric literature in this area has shown (see Bento et al. (2009); Small and Dender (2007)), these elasticities are not the same owing to the fact that consumers respond to increases in fuel prices by both altering fuel consumption but also their demand for fuel economy. Ignoring this important difference in VMT and blended fuel output response, by instead specifying consumption over blended fuel directly, would imply larger and unrealistic changes in domestic blended fuel markets and consequently domestic fuel market leakage.

[3]The subscript i in equation (2.3.11) now indexes six land uses.

where Γ_F is set so that ethanol and gasoline are energy equivalent perfect substitutes. Our treatment of blended fuel production as energy equivalent perfect substitutes is similar to the approach taken by de Gorter and Just (2009) but contrasts with Khanna et al. (2008), who use a constant elasticity of substitution (CES) functional form for this sector. We believe such a functional form is overly restrictive given that the share parameters entering that function are not endogenous and instead fixed to calibration year data. Unlike de Gorter and Just (2009), however, we solve for the share of ethanol in the absence of the RFS, using the first-order conditions of the profit maximization problem when the RFS constraint is not present.

When the RFS is not binding or not present, the fuel blender's profit maximization problem implies:

$$\Gamma_F = \frac{P_E - \tau}{P_G}. \tag{B.2.5}$$

We can identify the share of ethanol in blended fuel, $\Theta = \frac{E}{F}$, such that the above condition holds. In this case the price of blended fuel in the baseline is given by: $P_F = (P_E - \tau)\,\Theta + P_G\,(1 - \Gamma_F\Theta) - t_F$, where t_F is a pre-existing fuel tax. In contrast, the price of blended fuel when the RFS is binding is given by: $P_F = (P_E - \tau)\,\theta + P_G\,(1 - \Gamma_F\theta) - t_F$, when the VEETC is renewed, and $P_F = P_E\theta + P_G\,(1 - \Gamma_F\theta) - t_F$, when the VEETC is allowed to expire.

When the VEETC is renewed, the change in the price of blended fuel due to the RFS is given by: $P_F^1 - P_F^0 = \theta P_E^1 - \Theta P_E^0 - \tau\,(\theta - \Theta) + (1 - \Gamma_F\theta)\,P_G^1 - (1 - \Gamma_F\Theta)\,P_G^0$, where superscripts denote post-policy (1) and baseline (0). However, when the VEETC is allowed to expire, the change in the price of blended fuel due to the RFS is given by: $P_F^1 - P_F^0 = \theta P_E^1 - \Theta P_E^0 + \tau\Theta + (1 - \Gamma_F\theta)\,P_G^1 - (1 - \Gamma_F\Theta)\,P_G^0$. Note that while, $\tau\,(\theta - \Theta)$ is very close to zero (the change in the share of ethanol in blended fuel, $\theta - \Theta$ is very small), $\tau\Theta$ is not, reflecting the fact that when the RFS is imposed the full change in the price of ethanol is now passed along to the consumer through the change in the price of blended fuel.

Ethanol is produced according to a Leontief production function:

$$E = \min\left\{\frac{Y_E}{\lambda_{E,Y}}, \frac{L_E}{\lambda_{E,L}}\right\} \tag{B.2.6}$$

where Y_E is corn used for ethanol production and L_E is expenditures on labor, and $\lambda_{E,Y}$ and $\lambda_{E,L}$ are exogenous parameters that determine much corn and labor are required to produce a unit of ethanol. Ethanol is actually a joint production process which produces, in addition to ethanol, 'co-products' which can be used in place of grains in livestock feeds. We consider four co-products, dried distillers grains, corn gluten meal, corn gluten feed, and corn oil which are used in food production.[4]

[4]We assume that these four co-products are produced in fixed proportion to the amount of ethanol produced and are combined, in terms of corn and soybean equivalents, with the corn and soybeans used in food production. The value of co-products, which is endogenous, is taken as a rebate to the ethanol producer, and therefore subtracted from the marginal cost of producing ethanol.

Gasoline production is modeled with a nested constant returns to scale CES technology:

$$G(R_G, L_G) = \gamma_G \left[\alpha_G R_G^{\frac{\sigma_G - 1}{\sigma_G}} + (1 - \alpha_G) L_G^{\frac{\sigma_G - 1}{\sigma_G}}\right]^{\frac{\sigma_G}{\sigma_G - 1}} \tag{B.2.7}$$

where α_G is a share parameter, γ_G, is a scale parameter, and σ_G is the elasticity of substitution.

World Crop Demand

The rest-of-world consumption of US agricultural products is specified according to inverse excess (or import) demand functions:

$$P_i = \gamma_i \left(Q_i^{\frac{1}{\eta_i}}\right) \tag{B.2.8}$$

where Q_i is the amount of crop i demanded (net of supply) by the rest of the world, γ_i is a scale parameter for the crop i demand function, and η_i is the rest-of-world excess demand elasticity for crop i. Here i corresponds to trade in agricultural products with respect to the rest of the world, that is i spans corn, soybeans, wheat, and cotton. Given changes in crop exports, we impute how cropland expands at the expense of non-agricultural land uses, A_N, in the rest-of-world economy.

World Crude Oil Supply

We consider a simple model of crude oil supply that abstracts from market power considerations with respect to the production and refinement of crude oil. We specify the inverse rest-of-world excess (or export) supply of crude oil as:

$$P_R = \gamma_R \left(R^{\frac{1}{\eta_R}}\right) \tag{B.2.9}$$

where R is the amount of crude oil (net of demand) supplied by the rest of the world, γ_R is a scale parameter, and η_R is the rest-of-world excess supply elasticity for crude oil.

Food Production

Food production is modeled as a set of nested constant returns to scale CES functions:

$$\begin{aligned}
X(Y_i, L_X) &= \gamma_X \left[\alpha_X L_X^{\frac{\sigma_X - 1}{\sigma_X}} + (1 - \alpha_X) Q(Y_i)^{\frac{\sigma_X - 1}{\sigma_X}}\right]^{\frac{\sigma_X}{\sigma_X - 1}} \\
Q(Y_i) &= \gamma_Q \left[\alpha_{Y_3} Y_3^{\frac{\sigma_Q - 1}{\sigma_Q}} + \alpha_{Y_4} Y_4^{\frac{\sigma_Q - 1}{\sigma_Q}} + (1 - \alpha_{Y_3} - \alpha_{Y_4}) V(Y_1, Y_2)^{\frac{\sigma_Q - 1}{\sigma_Q}}\right]^{\frac{\sigma_Q}{\sigma_Q - 1}} \\
V(Y_1, Y_2) &= \gamma_V \left[\alpha_V Y_1^{\frac{\sigma_V - 1}{\sigma_V}} + (1 - \alpha_V) Y_2^{\frac{\sigma_V - 1}{\sigma_V}}\right]^{\frac{\sigma_V}{\sigma_V - 1}}
\end{aligned} \tag{B.2.10}$$

where L_X is the amount of labor used in food production, Q is a composite feedstuffs index including the four food crops and co-products, V is a composite index including corn, soybeans and co-products, Y_i is the amount of crop i needed to produce food.[5] σ_X, σ_Q, and σ_V are elasticities of substitution, α_X, α_{Y3}, α_{Y4} and α_V are share parameters, and γ_X, γ_Q and γ_V are scale parameters. Here, Y_1 and Y_2 are corn and soybeans used by the food sector net of ethanol co-products.

B.3 Data and Calibration

Benchmark Economy

Table B.1 presents the characteristics of the US economy for the calibration year, 2003. We chose to calibrate using 2003 data because it precedes several anomalous years prior to our period of analysis, where crop and crude oil prices were well above historic levels. Also, our primary data source for agricultural input data, the USDA's Economic Research Service (ERS) *Agricultural Resource Management Survey* (ARMS), is conducted for each major crop on a rotating quadrennial basis and 2003 is the central year of a recent four year cycle. In 2003, US GDP was roughly \$7.7 trillion. This includes net government transfers to households of \$2.9 trillion, which we assume here is financed from revenue raised from a uniform tax of 36.6% on the representative agent's labor endowment. This implies an after-tax value of the labor endowment of \$4.8 trillion.[6] The net returns from land holdings comprise the remainder of GDP, \$27.6 billion, which is small in comparison to total GDP.

In 2003, 112.68 million hectares of cropland were allocated to the five crops considered. These crops represent more than 90% of principle cropland harvested and more than 80% of the value of field crop production in 2003 according to USDA National Agricultural Statistics Service (NASS) data. Corn was the dominant crop in terms of land area, at 31.37 million hectares, followed by soybeans, hay, wheat and cotton. In addition to cropland, 13.57 million hectares were held as CRP. This is the sum of land held in the general sign-up and continuous non-CREP CRP programs and accounts for close to 95% of total land held as CRP, according to the USDA's Farm Service Agency *Conservation Reserve Program Statistics* (CRPS). We intentionally exclude those categories of CRP land which are not likely to be converted back into crop production, given the higher rental payments that are received or the services they provide, such as rare habitat conservation, riparian buffers, etc. The average CRP rental rate was \$114.48 per hectare.[7] Crop prices represent national average prices (paid to the farmer) reported to the USDA's National Agricultural Statistics Service (NASS). Average yields in the US for corn, soybeans, hay, wheat and cotton are also from NASS.

Blended fuel consumption in 2003 was 499.97 billion liters, of this regular gasoline made up 490.28 billion liters. This implies that 3.12 billion barrels of crude oil was used for gasoline in 2003, which is consistent with the US Energy Information Administration's (EIA) *US Crude Oil Supply & Disposition* (CSD) dataset. Total ethanol consumption was 10.39 billion liters according to the US Federal Highway Administration's *Highway Statistics 2003* (FHWA). The price of regular gasoline, \$0.23 per liter, is the consumption weighted US average spot price for all grades of conventional gasoline from the EIA's *Annual Energy*

[5] The crops are indexed as follows, corn ($i = 1$), soybeans ($i = 2$), hay ($i = 3$), and wheat ($i = 4$).

[6] These figures were taken from the US Bureau of Economic Analysis *National Income and Product Accounts* (NIPA) dataset.

[7] This value was computed from the CRPS and represents the weighted average annual rental payment to land in the general sign-up and non-CREP continuous sign-up programs.

Review 2008. We compute a spot price for ethanol in 2003 of \$0.35 per liter, which is the marginal cost of ethanol production less the value of co-products sold to food producers. This is very close to the average 2003 spot price for deliveries to Omaha, Nebraska of \$0.36 per liter according to Nebraska's *Unleaded Gasoline and Ethanol Average Rack Prices* data.[8] Given benchmark quantities and prices of gasoline and ethanol, the 2003 price of blended fuel is \$0.41 per liter, inclusive of the VEETC.

Consumer

We specify elasticities of substitution between miles and non-mile expenditures, σ_U in (B.2.1), of 0.50, between food and the composite good, σ_W in (B.2.1), of 0.09, and between fuel and non-fuel expenditures on driving, σ_M in (B.2.1), of 0.21. We selected these in order to imply a calibrated own-price elasticity of demand for food of -0.12, an own-price elasticity of demand for blended fuel of -0.34, and a cross-price elasticity of demand for VMT with respect to the price fuel of -0.22.

Estimates of the own-price elasticity of food demand are sparse. Our estimate is roughly consistent with the estimates of Seale et al. (2003), who report own-price elasticity for a broad consumption group of "food, beverages and tobacco" in the range of -0.075 to -0.098. We adopt a slightly more elastic value then the upper bound from that study, given that the own-price demand elasticity for tobacco is likely very small and is not represented in our treatment of the food sector here.

Our calibrated own price elasticity of demand for blended fuel is consistent with empirical estimates. In particular, our estimate is slightly lower than the best estimate proposed by the US Department of Energy of 0.38 (DOE, 1996), and considerably smaller than the central value of 0.55 assumed by (Parry and Small, 2005). We choose a smaller value in order to be consistent with more recent estimates which report a smaller value (Small and Dender, 2007).

Our calibrated own-price elasticity of demand for miles with respect to the price of blended fuel is well within the central estimates provided by the literature and is consistent with the value implied by Parry and Small (2005). Summaries of this literature (see De Jong and Gunn (2001); Graham and Glaister (2002); Goodwin et al. (2004)) report means for short-run estimates between -0.10 and -0.26 and long-run estimates of -0.26 and -0.34.

Given calibration year crop production and export shares, and the total value of food, this implies the representative agent spends 0.035 of their income on food. Given calibration year data on fuel prices, fuel quantities, and miles-traveled, and assuming that the share of fixed costs of driving to total costs of driving was 0.60, this implies that the share of income spent on VMT was 0.065. We note that these expenditure shares are lower than those computed from the US Bureau of Economic Analysis' (BEA) for 2003 of 0.091 and 0.082 respectively.[9] However, we believe that precisely calibrating the relationship of fuel

[8] Historic ethanol price data is limited. Most spot prices for ethanol are reported as the price of free-on-board deliveries to various rural locations in the Midwest, where ethanol has historically been produced. Spot prices to locations outside of the Midwest exist only for the last few years. Since our spot price for regular gasoline reflects the national average, it is necessary to adjust the non-corn input expenditures accordingly.

[9] These small differences in expenditure shares are likely due to definitional differences between the national accounts data and those implied by our model. The food share from the BEA is total expenditures in the 'Food' sub-heading divided by total GDP, less net exports. The VMT share is the sum of 'Motor vehicle and parts', 'Gasoline, fuel oil, and other energy goods', and 'Transportation' sub-headings divided by total

prices to the price of miles-traveled and the relationship of crop prices to the price of food is of greater importance for determining the equilibrium price effects of RFS. [10]

Fuel Production

The ratio of the energy content of ethanol to gasoline, $\Gamma_F = 0.66$, is based on the low heating values of each fuel. Our linear specification for the production of blended fuel is not calibrated to an estimate of the elasticity of blended fuel. Rather, the elasticity of blended fuel will be determined only by the underlying elasticities of gasoline and ethanol.

Gasoline Production

We assume an elasticity of substitution between crude oil and labor in the production of gasoline, σ_P, of 0.06. This was selected to approximate a perfectly complementary relationship between crude oil and labor in the production of gasoline.

The price of gasoline faced by the fuel blender is calibrated to the average spot price for conventional, regular grade gasoline in 2003.[11]

Ethanol Production

The per unit ethanol input requirements in equation (B.2.6), are calibrated to reflect an average ethanol production facility in the US. In 2003, we assume that the corn to ethanol conversion ratio is 2.56 kg per liter (GREET 1.8c Wang (2009)). We also assume that with each liter of ethanol co-products equivalent to 0.7 kg corn and 0.03 kg soybeans are produced (GREET 1.8c Wang (2009)).

To construct parameters for a national average ethanol producer, we consider four ethanol production technologies, which are combinations of conversion technology (wet or dry milling) and fuel source (natural gas or coal). These categories are used because wet milling and dry milling are inherently different technologies, produce different co-products and have different corn and energy requirements. In 2003, dry mills fired by natural gas and coal account for 39.4% and 12.9% of total ethanol production respectively. Wet mills fired by natural gas account for 5.4% of total production and wet mills fired by coal make up the remaining 42.3%. These shares are derived from ethanol plant start up dates reported by the EPA (2010).

Labor inputs to ethanol production are calculated as total expenditures on energy, transportation costs, labor and capital for ethanol production. Following Farrell et al. (2006), we assume that the energy requirements of ethanol production are 13.2 MJ/liter, which represents a combination of natural gas, coal and electricity. Average expenditures on labor and capital for ethanol production are assumed to be 0.0053 $/liter and 0.063 $/liter. These values are consistent with values reported by an industry survey (Shapouri and Gallagher, 2005).

GDP, less net exports.

[10] Another source, which although more dated provides a finer definitional resolution for making comparisons, is the BEA's *Benchmark Input and Output Tables for 1992*. This dataset provides expenditure shares of 0.041 and 0.055, respectively, which are markedly closer to our estimates.

[11] Average here means population weighted average price of PADDs 1, 3, and 5. PADDs 1, 3, and 5, are considered as these are the PADDs for which spot price data is readily available. Combined these three PADDs account for 69% of the total US population.

We estimate the quantity of co-products produced per unit ethanol using equations from GREET 1.8c Wang (2009). In the benchmark 0.52 kg of distillers' grains, 0.03 kg of corn gluten meal, 0.13 kg of corn gluten feed and 0.02 kg of corn oil are jointly produced with each unit of ethanol. Consistent with the EPA (2010), we assume a kilogram of distiller's dried grains displaces 0.95 kilograms of corn and 0.05 kilograms of soybeans. A kilogram of corn gluten feed displaces 1.53 kilograms of corn and a kilogram of corn gluten meal displaces 1.0 kilograms of corn. We allow corn oil to displace corn based on its economic value in 2003, such that \$1 of corn oil displaces \$1 of corn.[12]

Transportation costs incurred by the ethanol producer are also accounted for. First, we assume that the cost of shipping ethanol to its final destination is incurred by the ethanol producer. The cost of shipping ethanol is \$0.032 per liter, which is the PADD average tariff plus rate plus fuel surcharge per liter ethanol weighted by PADD level ethanol consumption. We also assume that the cost of shipping co-products to their final destination is subtracted out from the revenue the ethanol producer receives from selling co-products. The average cost of shipping co-products is 0.029 \$/kg, in constant 2003 dollars. This value is calculated using data on rail costs for transporting DDGs from data compiled by the USDA.

We estimate transportation costs based on USDA data for the average tariff rate plus fuel surcharge per liter ethanol delivered to each PADD, and the rail costs for transporting co-products. Both data series are compiled by the USDA from freight companies (BNSF, UP, CSX, and NS) websites for May 2010. To calculate the average ethanol transportation costs from the USDA data, we approximate the percent of the national total refinery and blender net inputs of fuel ethanol by PADD using data from the EIA on Refinery and Blender Net Inputs of Fuel Ethanol by PADD for the years 2000-2009. To calculate the average costs of shipping co-products from the USDA data, we take an average across all data points and assume that 30% of co-products are transported locally at zero cost to the ethanol plant.[13]

RFS Share Mandate

The RFS share mandate, θ_F, is computed by partially solving the model while treating several of the model outputs from the estimated baseline as fixed. First, we predict the amount of corn required to meet the additional production of ethanol given the quantity of ethanol mandated by the RFS. From this estimated change in corn production, we estimate the resulting change in crop prices, as well as the change in the net returns to the land endowment. From the change in the price of corn, impute the resulting change in the price of ethanol, regular gasoline and crude oil, and thus also the change in the price of blended fuel and VMT. Using these projections, we are able to generate an estimate of final total blended fuel demand, conditional on the RFS. Dividing the published RFS volumes by estimated total blended fuel demand identifies an estimate of θ_F.

[12] We use this method because corn oil is utilized for much more than just an animal feed, and therefore the typical displacement ratio methods used are not reflected in the historic prices of the two products (Shapouri and Gallagher, 2005).

[13] The USDA data reports the tariff rate plus fuel surcharge per unit of co-products between various origin and destination cities.

Food Production

All crops that are not used for ethanol production or exported are used to produce food. The share of crop expenditures on food to the total value of food, 0.19, is taken from the USDA ERS *Marketing Bill and Farm Value Components of Consumer Expenditures for Domestically Produced Farm Food*, as the value of farm products per food dollar spent. This assumption allows us to the benchmark value of labor used in food production, L_X.

The elasticities of substitution, σ_X, σ_Q and σ_V, in the food production function (Equation (B.2.10)) are provided in Table B.5. These parameters are selected to reflect the technical properties of food production. In particular, we choose σ_X to reflect near complementarity between crops and labor in the production of food. This prevents substitution from crops to labor that is unrealistic. We allow for much greater substitutability between hay, wheat and the corn-soybean index V, and the greatest substitutability between corn and soybeans. In 2003, the resulting own-price elasticities of crop demand for domestic food production range from -0.16 to -0.22 for the four crops used in food production which are broadly consistent with literature estimates for developed countries (see FAPRI *Searchable Elasticity Database*). In the text, we perform sensitivity analysis on the elasticities of substitution in the food production function to vary the implied crop demand elasticities for food production.

Land Use Allocation

To construct the per-unit land labor expenditures for agricultural production (l_i in equation (2.3.11)), we sum expenditures over four broad input categories: labor, capital, energy and fertilizer (Table B.4). Expenditures on labor and capital are from the USDA's ERS *Commodity, Costs and Returns* (CCR) dataset. Capital expenditures include interest on operating capital and the capital recovery of machinery and equipment. Labor expenditures include the wages and the opportunity costs of unpaid workers.

We construct energy and fertilizer expenditures from detailed input use data and subsequently use this data to calculate crop specific emissions factors (discussed below). Our estimates for energy expenditures are aggregate expenditures on diesel, gasoline, natural gas, electricity and liquefied petroleum gas. Diesel use for each crop was derived from West and Marland (West and Marland, 2002) and Nelson et al. (Nelson et al., 2009). Crop specific use of the other energy sources were derived from the lifecycle analysis literature (Farrell et al., 2006; Hill et al., 2006; Piringer and Steinberg, 2006). Fertilizer expenditures represent expenditures on all variable inputs that are not categorized as energy, capital or labor and are constructed from two main sources. First, expenditures on nitrogen, phosphorus, and potassium fertilizer, pesticide and seed are calculated using crop level input use data from ARMS and national prices from the USDA's ERS *Fertilizer Use and Price* data.[14] Second, expenditures on other variable inputs are from the CCR.[15] Fertilizer expenditures are disaggregated in the lower panel of Table B.4.

[14] Input data for hay is not available in the ARMS, so fertilization rates were collected from extension reports from institutions in major hay producing regions. Application levels were based on recommendations given a medium or optimal soil test.

[15] This includes expenditures on soil conditioners, manure, custom operations, repairs, purchased irrigation water, taxes and insurance, and general farm overhead.

Land Supply Elasticities

The six δ_i in (B.2.3) are selected in order to match the supply response of the US land market to the elasticities taken from the literature and reported in Table B.3. Given the six δ_i, we select the six β_i in (B.2.3) in order to match the yields reported in Table B.1 in 2003, and adjusted each year afterwards to reflect exogenous growth in crop yields over time (see Section B.5 below). Given the structure of the model, these β_i can be solved for as a function of δ_i such that the implied yields are almost identical to the targeted yields. To improve precision in matching estimated supply response to literature estimates, we re-calibrate the δ_i parameters each year to construct our baseline, and then again for each counterfactual run.

To select each δ_i vector, we perform an exhaustive search that seeks to minimize the error between the supply response implied between two model runs (taking the equilibrium resulting from the previous run as exogenous data) and the supply response implied by Table B.3 given the percent change in crop prices between the two model runs. Each search is highly non-linear and takes several days to complete. To improve computational time and precision, we exploit several optimization algorithms, including modern heuristic algorithms such as the Local Multistart Radial Basis Function (LMSRBF) algorithm developed by Regis and Shoemaker (2007). We repeat this using multiple random re-starts and choose the vector that achieves the best supply response from the resulting candidates. The initial 2003 δ_i vector was selected to match supply response resulting from a 1% exogenous increase in ethanol. All baseline δ_i vectors are selected recursively using the preceding year's baseline equilibrium as exogenous data, starting from the 2003 baseline equilibrium. Each counterfactual δ_i vector for a given year is selected using the baseline equilibrium for that year as exogenous data. We isolate the δ_i vector for each baseline run using a baseline in which the VEETC is in place. We isolate the δ_i vector for each counterfactual run for our first regime which compares the RFS with the VEETC to the baseline in which the VEETC is in place. In total, these searches took about six months to complete.

To demonstrate the success of this approach, we point to the exhaustive validation exercise we perform in Section B.7 that attempts to demonstrate that the predicted land response of our model is in line with observed outcomes. We match observed land patterns well and our predictions for later years are in line with USDA Long-Term projections that pre-date the RFS.

Rest-of-world Crude Market

The model framework presented above considers the excess supply of crude oil going to the US for gasoline consumption, R. To calibrate the elasticity of excess supply facing US gasoline producers and to calculate the impact of the RFS on rest of world crude oil consumption we rely on a simple model of the international crude oil market. An important feature of our framework is that we incorporate all US crude oil demand for purposes other than gasoline production, as well as all US supply of crude oil, in our specification of the international crude oil market. This assumption simplifies the numerical model and the exposition of leakage sources.[16]

[16] Separating US demand for crude products in this manner is a definitional assumption only. As discussed in the next section, the excess supply elasticity faced by US gasoline producers is calibrated to account for

Imposing market clearing in the international market for crude oil implies:

$$R = D_{Gas}^{US} = S_{Crude}^{ROW} + S_{Crude}^{US} - D_{Crude}^{ROW} - D_{Dist}^{US} - D_{Other}^{US} \tag{B.3.1}$$

where, D_{Gas}^{US} is the amount of crude oil demanded for gasoline in the US market, D_{Dist}^{US} is the amount of crude oil demanded for distillate fuels in the US market, D_{Other}^{US} is the amount of crude oil demanded for all other crude products (which includes residual fuels, jet fuel, kerosene, LPG and other petroleum products) in the US market, D_{Crude}^{ROW} is the amount of crude oil demanded in the ROW market (for all products), S_{Crude}^{ROW} is the amount of crude oil supplied by the ROW, and S_{Crude}^{US} is the amount of crude oil supplied by the US.[17]

Differentiating this equation with respect to the price of crude oil and solving for the elasticity of excess supply facing US gasoline producers, η_R, we have:

$$\begin{aligned} \eta_R = \eta_{S,Crude}^{ROW} \left(\frac{S_{Crude}^{ROW}}{D_{Gas}^{US}} \right) + \eta_{S,Crude}^{US} \left(\frac{S_{Crude}^{US}}{D_{Gas}^{US}} \right) \\ - \eta_{D,Crude}^{ROW} \left(\frac{D_{Crude}^{ROW}}{D_{Gas}^{US}} \right) - \eta_{D,Dist}^{US} \left(\frac{D_{Dist}^{US}}{D_{Gas}^{US}} \right) - \eta_{D,Other}^{US} \left(\frac{D_{Other}^{US}}{D_{Gas}^{US}} \right). \end{aligned} \tag{B.3.2}$$

To calibrate η_R using (B.3.2) we use data for 2003 quantities from the EIA's International Energy Statistics. The quantities for each of these components of the crude oil market, following the decomposition above, as well as the shares of each component to the quantity of crude demanded for gasoline in the US is reported in the first two columns of Table B.6. In 2003, total world crude considered in our framework is 4,545.8 billion liters (28,954 million barrels). [18] The rest of the world is the primary supplier of crude oil, contributing 4,046.2 billion liters while the US supplies 499.6 billion liters. On the demand side, ROW crude demand totals 3,419.5 billion liters. US crude oil demand makes up the remainder, with roughly 44% (490.3 billion liters) of total US crude oil demand going to gasoline production.

The final column in Table B.6 reports the central literature values for the elasticities on the right-hand side of (B.3.2) as well as the resulting elasticity of excess supply facing the US gasoline producer (first row), η_R. We use short-run elasticity estimates from the literature because these elasticities are used to quantify the annual response to a change in the yearly average price of crude oil. In this time frame, we can expect both supply and demand adjustments, such as as adjustments in operable crude oil refinery capacity or oil recovery and transportation infrastructure, to be relatively fixed.

We chose elasticities for the US and ROW supply of crude oil of 0.045 and 0.035, respectively. The resulting elasticity of total world crude supply is 0.037 which is consistent with values estimated and used by the literature which range from 0.01 to 0.06 (Krichene, 2002;

US crude demand for purposes other than gasoline production and should therefore have no impact on the overall adjustments in US or ROW crude oil demand.

[17] We use EIA definitions regarding the quantity of crude oil going to the the production of each petroleum product.

[18] Our estimate here is slightly below (138 million barrels) the EIA estimate of total world crude consumption because we ignore gasoline used for non-transportation purposes in the US. Keeping the market shares constant, we adjust the total size of the crude market to reflect this difference. As a result, the quantities reported in Table B.6 will be slightly below the values reported by the EIA.

Smith, 2009; OECD, 2004). Given what appears to be a structural change in this market since at least 1973, we give greater weight to analyses that use more recent data, which appear to suggest smaller elasticities, especially with respect to OPEC sourced crude oil, than in the past. We choose a slightly higher elasticity for US supply than ROW supply; an assumption that is supported by the literature (Ramcharran, 2002; Greene, 2010).

Our value for the elasticity of world crude oil demand, -0.02, is within the range of elasticities found in the literature. Estimates, and values used in the literature, of the elasticity of crude oil demand range from -0.01 and -0.17, with most estimates falling in the range of -0.02 to -0.06 (Krichene, 2002, 2005; OECD, 2004; Gately, 1984; Gately and Huntington, 2002). In our model, the elasticity of ROW crude demand is used to calculate the change in rest of world crude oil use. A number of studies (Gately and Huntington (2002); Dargay and Gately (1995, 2010)) have noted that the demand response for crude products to changes in crude prices, particularly in developed countries, is more limited for price decreases than price increases. Since the RFS will always decrease the price of crude oil, we select a conservative estimate closer to the lower end of the estimates reported in the literature to reflect this asymmetry.

In the absence of comparable short-run estimates for crude demand for distillate fuels and other petroleum products we use an elasticity of -0.02 for each of these components of demand. Since these two components, in addition to total ROW demand for crude oil together make up 90% of total world crude oil demand, it is reasonable to expect that the net elasticity across these components will be very close to the elasticity of world crude demand.

Given our chosen elasticity values and the 2003 quantities of each crude oil market component, we calibrate (B.2.9) to reflect an excess supply elasticity for crude oil of 0.5 in our central case. As discussed, there is a broad range of estimates for elasticities of crude oil supply and demand in the literature. To account for this range, we consider values of 0.25 and 0.75 as lower and upper bounds for η_R in sensitivity analysis. One possible way to think about these bounds, would be to proportionally scale the corresponding elasticities for rest-of-world demand and supply of crude oil. For example, when we impose an elasticity of excess supply elasticity of 0.75 the elasticity of rest of world crude crude oil demand of -0.03

Two considerations are important for comparing our crude oil elasticities to other biofuel studies. First, our model measures the annual impact of the RFS on greenhouse gas emissions and we therefore use short run elasticities for crude oil supply and demand. Our elasticities should, and do, differ from those used by studies that analyze the aggregate impact of the RFS over many years and therefore use medium to long run elasticities (Rajagopal et al., 2011; Thompson et al., 2011). Second, the elasticities we specify are for the supply and demand of crude oil and should not be directly compared to the elasticities of gasoline supply and demand used elsewhere (Chen and Khanna, 2012; Drabik and de Gorter, 2011).

Rest-of-world Crop Demand

The crop export demand elasticities, η_i in equations (B.2.8), are set to -0.65, -0.60, -0.55, and -0.75 for corn, soybeans, wheat and cotton respectively, which represent the central values reported in Gardiner and Dixit (1987).

Rest-of-world Land Use

In absence of a fully specified world land use model, we linearly relate reductions in US crop exports to reductions in world agricultural land. Specifically, we assume that 44%, 50%, 47% and 50% of reduced US corn, soybean, wheat and cotton exports are replaced by expanded agricultural production in the rest of the world at non-US average yields. These shares are given by:

$$\gamma_{ROW,i} = \frac{-\eta^{ROW}_{S,i} S_i}{\eta^{ROW}_{D,i} D_i - \eta^{ROW}_{S,i} S_i} \tag{B.3.3}$$

where $\eta^{ROW}_{S,i}$ and $\eta^{ROW}_{D,i}$ are the rest-of-world elasticities of supply and demand for crop i, and D_i and S_i are the rest-of-world demand and supply for crop i. The elasticity values are taken from the FAPRI *Searchable Elasticity Database* and the supply and demand quantities are 2003 values reported by the USDA's Foreign Agricultural Service (FSA) *Production, Supply and Distribution Online* (PSD) dataset.

In our central case, the percentages of reduced US crop exports replaced by expanded agricultural production are broadly consistent with range of values implied by earlier studies by Searchinger et al. (2008) and the US EPA (2010).[19] More recent studies, such as Hertel et al. (2010), argue that the earlier analyses overestimate world land use change because they fail to account for factors that may mitigate a portion of the expansion in world agricultural production such as price induced yield improvements and crop demand adjustments. To address the uncertainty in the literature, as sensitivity analysis we consider high and low cases where the percentage of US crop exports replaced by expanded world production for each crop are increased and decreased by 20% from the central value. The high case represents a world with a more inelastic world demand for agricultural products and where yields respond inelastically to price increases. The low case represents the case where reductions in crop demand and price induced yield improvements soften the link between reduced US exports and rest-of-world land use change.

B.4 Emissions Calculations

The emissions factors corresponding to the ϕs in equations (2.3.18) are (2.3.19) are presented in Table B.7 and are described in detail below. For each product or activity, we account for the release of three major greenhouse gases, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) measured in units of carbon dioxide equivalents (CO_2e).[20] For all emissions factors, we abstract from infrastructure related emissions. For example, we measure the emissions from the operation of an ethanol production facility, but do not include emissions from the construction of, or the raw materials used to construct, the facility itself. As a result, our emissions system boundary is slightly more restrictive than that of earlier lifecycle analyses (see for example, Farrell et al. (2006); Hill et al. (2006)), but consistent with the US EPA (2010).

[19] The results of Searchinger et al. (2008) imply that 50%, 82% and 52% of reduced US corn, soybeans and wheat exports are replaced by expanded production worldwide. Similar percentages are implied in the US EPA (2010) study for corn and soybeans in 2015, 65% and 67% respectively. However, world land allocated to wheat declines in this year, despite reduced US wheat exports.

[20] We use global warming potentials from IPCC Third Assessment Report to calculate CO_2e.

Overview

The emissions coefficient for gasoline, ϕ_G, is inclusive of the emissions from both gasoline consumption and production. In contrast, we consider only the emissions from ethanol production, $\phi_{E,M}$, given that the carbon stored in ethanol, and released during ethanol combustion, is absorbed from the atmosphere during the growth of corn (IPCC, 2007). The agricultural production emissions coefficients, ϕ_Y and ϕ_Z, include emissions from the production of agricultural inputs, such as fertilizer, as well as on-farm emissions.[21] All of these emission coefficients, as well as the coefficient on crude oil, ϕ_R, are positive, reflecting the fact that these activities generate GHG emissions. In contrast, the emissions coefficients of non-agricultural land uses, $\phi_{N,k}$, are negative, reflecting the annual emissions benefits from the uptake of atmospheric carbon by biomass (such as the growth of forest or grasslands) and through increased carbon sequestration in soils (Fargione et al., 2008). These benefits are lost when non-agricultural land is brought into agricultural production. The carbon benefits of non-agricultural land differ between the two countries, because the carbon stocks of CRP are limited because these lands have historically been cleared for agricultural production, and tend to be held as grasslands, while it is likely that expanded agricultural production in the rest of the world will take place at the expense of previously undisturbed lands with much larger carbon stocks, such as forests or shrubland (see for example EPA (2010), Searchinger et al. (2008) and Fargione et al. (2008)).

Gasoline

The lifecycle emissions of gasoline, ϕ_G, are 3.0 kgCO_2e/liter, which is the baseline lifecycle emissions for US gasoline estimated by NETL (2008). This factor is used by the EPA in the Regulatory Impact Analysis of the RFS, as well as the RFS Final Rule, and includes emissions from crude oil extraction, transport and refining, the transportation and distribution of finished gasoline, and tailpipe emissions (NETL, 2008).

Ethanol Production and Combustion

The lifecycle emissions from ethanol production are assumed to be 0.6 kgCO_2e/liter. This factor assumes a representative natural gas fired dry-mill ethanol plant, consistent with the US (EPA, 2010). We also account for the release of CH_4 and N_2O from ethanol combustion, which totals 0.02 kgCO_2e/liter (EPA, 2010).[22] Combining, ϕ_E is 0.62 kgCO_2e/liter.

We consider only natural gas fired ethanol production for our emissions analysis because the construction of additional coal fired ethanol production facilities is likely to be limited by the RFS legislation, because ethanol produced by these facilities is unlikely to achieve the 20% lifecycle emissions reduction threshold (EPA, 2010). While we do account for the make up of US ethanol production in the economic model, for our emissions analysis we consider the "marginal" or additional production of ethanol, which we assume occurs in natural gas fired dry mills. Our ethanol production emissions factor is notably lower than an US average emissions factor for ethanol production because coal fired ethanol production is not considered in our emissions analysis.

[21] These are emissions that arise from interactions between agricultural soils and farm inputs and fossil fuel combustion.

[22] While the CO_2 released during ethanol combustion is completely offset by carbon uptake during the growing of corn, this is not the case for other greenhouse gases.

International Crude Oil Consumption

To calculate emissions related to changes in rest of world crude oil consumption, we account only for the emissions from changes in crude used to produce gasoline and distillate fuels, and exclude changes emissions from crude going to other crude products (here defined as including residual fuel oils, jet fuel, LPG and other miscellaneous products). We are therefore considering emissions from approximately 47% of the world crude oil market.[23] Excluding emissions from other crude products is a conservative assumption that allows us to isolate adjustments in rest-of-world crude oil consumption related to the transportation sector that are most likely to have first-order implications for changes in greenhouse gas emissions resulting from the RFS. This assumption is discussed in detail below. For completeness, we also report a plausible upper bound of the impact on emissions related to changes in rest of world crude oil consumption by attaching positive emissions coefficients on other crude products. Even with this plausible upper bound, the main conclusions of our analysis are not affected.

Crude oil is refined into a variety of products that are used by several energy and industrial sectors. Other crude products are used predominantly as factors of production or for non-passenger vehicle transportation purposes, and may not be combusted (in the case of lubricants or crude used for manufacturing). Ideally, to compute the total change in emissions related to changes in crude oil, we would like to specify a detailed model of the energy and other end-use demand sectors that consume all crude products. This is beyond the scope of this paper, and, as such, we simply assume no change in emissions resulting from other crude products. This is a conservative estimate in the sense that we are assuming the smallest possible change in emissions related to transportation sector adjustments.

To understand why this is, consider the following example of how one would ideally like to compute the change in emissions for one portion of other crude products, residual fuel oil, which is consumed by the electricity sector or by industrial users for energy purposes. Equilibrium in the market for electricity is characterized by:

$$D_{Elect} = S_{Resid} + S_{Other} \tag{B.4.1}$$

where: D_{Elect} is total demand for electricity, S_{Resid} is the amount of residual fuel oil supplied by crude refiners for electricity generation, while S_{Other} is the quantity of electricity supplied by sources other than residual fuel oil. If the RFS lowers the price of gasoline, there will be two adjustments in this market that result, a demand-side adjustment, and a supply-side adjustment.

In the case of a demand-side adjustment, a fall in the price of gasoline will lead to a fall in the price of crude oil and consequently the price of electricity. This will push up the left-hand-side of (B.4.1), total demand for electricity, leading to additional emissions. However, demand-side adjustments are likely to be very small for the final end-use of energy, since the elasticity of demand in these sectors tends to be very small. For example, residential demand for energy has been found to be very inelastic, particularly in developed countries and in response to price reductions (Haas and Schipper, 1998). Since demand-side adjustments are

[23] In 2003, total crude used for purposes other than US gasoline production totaled 4,055 billion liters. Of this, US distillates totaled 5.5% while ROW gasoline and distillates totaled 16.2% and 25% respectively.

likely to be small, the increase in emissions due to these adjustments will also be small.

With respect to the supply-side, note that a fall in the relative price of S_{Resid} as a result of the RFS, will lead to substitution from S_{Other} to S_{Resid}, given no change in D_{Elect}. At the margin, this will imply a reduction in emissions from S_{Other} together with an increase in emissions from S_{Resid}. If the crude product displaces a dirtier alternative then this supply-side substitution will result in a slight decrease in emissions. However, if the crude product displaces a cleaner alternative, then this supply-side substitution will imply an increase in emissions. In the case of electricity markets, the alternative will most likely be natural gas or other renewable sources, which is a cleaner alternative relative to residual fuel oil, and so this supply-side margin of adjustment will imply more emissions.[24]

Since both demand and supply-side adjustments in the electricity market are likely to lead to emissions increases, our approach which ignores them entirely will be conservative. Finally, while we have considered the case for residual fuel oil in our hypothetical exposition here, we note that with respect to the other three components of other crude products (jet fuel, LPG and other miscellaneous products), that similar arguments persist. In the case of 'other petroleum products', which account for roughly a third of other crude products, many of these products are used as lubricants or for chemical manufacturing and not actually combusted. Therefore, the emissions impact will be virtually negligible irrespective of demand or supply-side adjustments.[25]

Crude Oil Emissions Factors

To calculate the emissions from rest-of-world crude oil consumption, we account for changes to each component of the world market for crude oil separately (as discussed above) using fuel specific emissions factors from the EIA's Voluntary Reporting of Greenhouse Gases Program. These emissions factors capture only the direct release of CO_2 from the combustion of petroleum fuels, not the emissions resulting from the refining of crude oil into the final products.

In our central case, where we account for emissions only for changes in crude used for gasoline and distillate fuels, the average emissions factor for rest of world crude consumption is 2.6 kgCO_2e/liter (408 kgCO_2e/barrel). This represents the emissions per liter of distillate

[24] A recent study has shown that the demand for residual fuels has been highly responsive to the price of crude oil specifically because of the presence of non-crude energy sources, such as natural gas (Dargay and Gately, 2010).

[25] With respect to jet fuel, however, a few additional remarks are in order. As for the other cases, supply-side substitution is likely to be small owing to the low penetration of non-crude substitutes for jet fuel. However, demand for air transportation is complicated by the demand for transportation more broadly, which includes passenger vehicles as a possible mode. Air travel demand is generally more elastic relative to other modes, since most people do not use air transport to go to work or run errands (Dargay and Gately, 2010). What we are abstracting from in this case is the equilibrium adjustment in transportation mode choice as the RFS makes air transportation relatively more attractive relative to automotive transport. Computing the net impact on emissions from such switching is complicated, since it requires assumptions regarding the extent of substitution between modes for various classes of trips, and is contingent upon occupancy rate. Estimates of emissions per mile traveled from automobiles, however, do not differ considerably from emissions from airplanes, and so such equilibrium changes in transport mode are not likely to have considerable first order impacts on emissions (http://www.buses.org/files/ComparativeEnergy.pdf). Since we ignore emissions from this category we again are being conservative since such emissions from these demand-side adjustments for jet fuel are likely to imply additional emissions.

fuels and motor gasoline weighted by the rest-of-world market shares of these fuels in 2003. The market shares for gasoline (32%) and distillate fuels (68%) are calculated using data from the EIA's International Energy Statistics. The emissions factor for crude used for gasoline production in the rest of the world is 2.4 kgCO_2e/liter (374.2 kgCO_2e/barrel). The emissions factor for distillate fuels is slightly higher 2.7 kgCO_2e/liter (426.3 kgCO_2e/barrel).

As part of our analysis of the emissions from the world crude market below, we also consider potential emissions from other crude products in the US and the rest of the world. This category is an aggregate of crude oil used for all products other than gasoline and distillates, including residual fuels, jet fuel, kerosene, LPG and other petroleum products as defined by the EIA. To these categories we assign emissions factors of 1.7 kgCO_2e/liter (266.5 kgCO_2e/barrel) and 2.1 kgCO_2e/liter (334.5 kgCO_2e/barrel) for the US and rest of world respectively.

We back out these emissions factors from the EIA International Energy Statistics reported total CO_2 emissions from petroleum production in 2003. First, for both the US and ROW we deduct from total 2003 CO_2 emissions, the CO_2 emissions from gasoline and distillate consumption calculated using the emissions factors described above and the 2003 quantities of gasoline and distillate consumption reported by the EIA. We then divide these quantities of CO_2 by the quantity of petroleum that we categorized as other crude products. This provides emissions per unit other petroleum products in both the US and ROW.

The difficulty in calculating emissions factors for our category of other crude products lies in assigning a level of emissions to the EIA defined other petroleum products, since this petroleum may not be combusted, but rather used as a manufacturing input or lubricant. Our method of deriving an emissions factor for our category of other crude products implicitly uses EIA assumptions regarding the composition of crude products in this category and their resulting emissions. That the emissions factors for are other crude category are lower than the emissions factors for gasoline or distillates is reasonable, given that the EIA defined category of crude is not necessarily combusted. In addition, our category of other crude oil products is made up of a large share of LPG (29.4% in US, 18.1% in ROW) which has an emissions factor that is 40% lower than that of gasoline or distillates (1.5 kgCO_2e/liter).

Analysis of Different Crude Oil Market Assumptions

While excluding the change in emissions arising from adjustments in other non-gasoline and non-distillate petroleum products affects the magnitude of leakage from the world crude oil market, it does not, in general, affect whether we predict the RFS to have a positive or negative impact on emissions. Table B.11 reports the net impact on emissions of the RFS for the years 2012 and 2015 under our central treatment of emissions from the rest of world crude market, as well as two alternative treatments. First, we account for emissions only for crude used to produce gasoline, both domestically and in the rest of the world. Since the gasoline used outside the US accounts for only about 16% of rest-of-world crude oil use, leakage from the world crude oil market is substantially lower than in our central case. Second, we report an estimate for the change in emissions owing to a change in demand for all crude products. This approach provides a plausible upper bound on emissions from adjustments in the world crude oil market, provided there are not significant demand-side adjustments.[26]

[26]The change in other crude products is net of both demand and supply-side adjustments. By capturing emissions from the change in the demand for other crude products we are assuming the change in emissions

When accounting for adjustments in all crude products, leakage from the world crude oil market roughly doubles relative to the central case, because other crude products are a considerable portion of the world crude market. With all of the approaches we consider for calculating emissions from the crude oil market, the RFS will increase emissions in 2012 and 2015 when the VEETC is renewed. Swapping the RFS for the VEETC will reduce emissions when only changes in crude of gasoline, or only crude for gasoline and distillates are considered in the emissions calculations, but have will a very small positive impact on emissions when all crude products are included in the emissions calculations.

Agricultural Production

To construct ϕ_Y and ϕ_Z we consider on-farm sources of emissions, which include agricultural N_2O and emissions from energy use and liming, as well as emissions from agricultural input production. In our central case, N_2O emissions from agricultural production are calculated using methods and default parameters from the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). These methods map nitrogen additions to agricultural soils, from synthetic fertilizers and crop residues, to N_2O emissions.[27] Crop specific synthetic fertilizer application rates are from our agricultural dataset. Nitrogen additions from crop residues are calculated using the crop yields from the economic model and crop-specific IPCC default parameters (IPCC, 2006).

Using the IPCC methods, the production of corn is more than twice as emissions intensive than each of the other crops and six times more emissions intensive than soybeans. Although the quantity of nitrogen additions is a major factor in quantifying N_2O emissions from agricultural production, other factors such as soil characteristics, previous crop, cropping practices and weather patterns can have a significant effect. As such, there is no agreed upon method for translating nitrogen additions to N_2O emissions.[28] To account for these uncertainties, as sensitivity analysis we adjust the agricultural emissions factors to reflect alternative methods for assessing N_2O emissions from agricultural production. For our low case, we use crop-specific N_2O emissions factors consistent with the US average of DAYCENT/CENTURY simulations used by the EPA (2010). Relative to the central case,

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from supply-side adjustments are of the dirtier crude product, hence this is a plausible upper bound with respect to supply-side adjustments. Since the change in other crude products also includes the change in other crude products from the demand side as well, with respect to the demand side we are only accounting for the increase in emissions from the other crude product and not the non-crude alternative. To the extent that demand-side adjustments also lead to significant increases in the non-crude alternative, we are still not counting these emissions, and hence this may not be an upper bound in this case. In order for this to be significant, however, we would require both a large demand-side increase in the end-use product as well as a large share of the non-crude alternative relative to the other crude product with small substitutability between the two inputs. With respect to the end-use sectors that consume other crude products, we think this is highly unlikely, and so on net, this should be thought of as a plausible upper bound.

[27]The IPCC methods also consider N inputs from organic fertilizer and sewer sludge. In the US, nitrogen inputs, and therefore N_2O emissions, from organic fertilizer and sewer sludge are small and are therefore not considered (EPA, 2009).

[28]For example, Crutzen et al. (2008) suggest that between 3-5% of the N in nitrogen additions to soil would be released as N_2O rather than the IPCC default of 1%. Crutzen et al. also find that total N_2O emissions calculated using the IPCC methods are consistent with their own analysis if all sources of N_2O emissions are considered, particularly livestock production and grazing.

emissions from soybean production are three times greater in low agricultural N_2O case.[29] In the high case, we use the upper bound recommendation of Crutzen et al. (2008) and assume 5% of nitrogen in nitrogenous fertilizer is converted to N_2O.

Emissions from agricultural energy use are calculated using the crop specific energy input requirements from our agricultural data set and lifecycle emissions factors for the agricultural use of each energy type estimated using GREET 1.8c (Wang, 2009). These factors include both emissions from the combustion of the fossil fuel plus the emissions from the production and transportation of the fuel. Emissions from lime application to agricultural soils are estimated using IPCC default methods which assume that all carbon in lime applied to agricultural soils is converted CO_2 (IPCC, 2006).

We use GREET 1.8c (Wang, 2009) to estimate the lifecycle emissions of producing nitrogenous (N), phosphate (P), and potassium (K) fertilizers, pesticide and agricultural lime. The farm input production lifecycle includes feedstock recovery and transportation, and the production and transportation of the final farm input.

The emissions from nitrogen production are 2.99 $kgCO_2e$ per kilogram nutrient N. This factor is estimated assuming a US average nitrogen fertilizer mix of 70.7% ammonia, 21.1% urea and 8.2% ammonium nitrate, which is based on USDA data. This emissions factor includes the emissions from producing the feedstock to fertilizer production (primarily natural gas) as well as the emissions from the production and transportation of the fertilizer itself. We use an emissions factor for the production of phosphate fertilizer of 1.04 $kgCO_2e$ per kg nutrient P. This factor includes the production, processing and transportation of sulfuric acid, phosphoric rock and phosphoric acid. Our emissions factor for the production of potassium fertilizer, which includes only the emissions from production and transportation of potassium oxide (K_2O), is 0.69 $kgCO_2e$/kg nutrient K. The lifecycle emissions of agricultural lime production are 0.63 $kgCO_2e$/kg lime and present the net emissions from mining, production and transportation. The emissions factor for the production of pesticide, 21.9 $kgCO_2e$/kg pesticide, represents the weighted average emissions from the production of four herbicides and a general insecticide.[30]

Domestic Land Use Change

We assume that the emissions from converting land held in CRP to cropland, $\phi_{N,D}$, are 2.3 $mgCO_2e$/ha. To calculate this factor we assume, following the EPA (2010), that the conversion of CRP land to cropland results in the immediate release of all carbon stored in the above-ground biomass on CRP land. In addition, the carbon stored in below-ground biomass and soils of CRP land is released within the next 30 years. Consistent with standard practice (see EPA (2010)), we amortize total emissions from land use conversion over 30 years, with no

[29]We refer to this as our low sensitivity case because it results in the RFS having a smaller net impact on agricultural emissions. This is primarily due to the increased emissions savings due to displaced soybean production. N_2O emissions from soybeans are substantially higher in the low emissions case because the DAYCENT/CENTURY models account for the nitrogen fixed by leguminous plants (soybeans).

[30]Crop specific shares of herbicide and insecticide to total pesticide are calculated from the ARMS. For each crop, the share of herbicide is greater than 90%. We use the GREET 1.8c assumptions for the herbicide mix applied to corn and soybeans, and assume herbicide applied to hay, wheat and cotton consists of equal parts of the four herbicides.

discounting.[31] We assume that CRP land is abandoned cropland planted to perennial grasses for 15 years (prior to conversion), having stored 30.51 mgCO_2e/ha in above and below ground biomass and 37.95 mgCO_2e/ha in soils (Fargione et al., 2008). We focus on the conversion of grasslands to cropland because while biomass on CRP land can take a number of different forms, in 2007 at least 77% of continuous signup CPR was classified as native or introduced grasses (FSA). Also, given the costs of converting forested land to cropland, it is CRP held in grassland that will likely be converted to cropland. If CRP lands converted to production sustained another type of land cover, for example native grasses or woody biomass, then the emissions consequences of conversion could be markedly higher (Fargione et al., 2008). On the other hand, the CRP targets marginal cropland with specific environmental benefits. If the land in CRP frequently moved in and out of agricultural production, or is degraded, the soils may have accumulated little soil carbon, and the emissions from converting the land back to cropland would be lower than our central estimate. To account for this uncertainty, we consider as sensitivity analysis the 95% confidence interval bounds for $\phi_{N,D}$ calculated with the standard deviation in total emissions released due to the conversion of abandoned cropland (24 mgCO_2e/ha) from Fargione et al. (2008).

World Land Use Change

As a central value, we assume that the emissions benefits lost as a result of the expansion of non-US cropland, $\phi_{N,W}$, are 8.0 mgCO_2e/ha (EPA, 2010). The emissions from world land use change are substantially larger than the emissions from domestic land use change. This is because cropland expansion in the rest of the world is predicted to displace previously undisturbed land cover with large carbon stocks. The international land use change emissions factors are derived from economic models used by the US EPA that predict the location (54 regions) and type (pasture, native ecosystems) of land converted to cropland as a result of the RFS for corn ethanol (EPA, 2010).[32] The economic results are further disaggregated spatially and into twelve land conversion categories, including forest, grassland, shrubland and savanna among others. Land use conversion patterns are estimated using historical satellite land use cover data. There is considerable heterogeneity in the greenhouse gas emissions consequences of converting different native ecosystems to cropland because of the variability in carbon stored by different ecosystem types. For example, tropical forests, on average, have larger carbon stocks than temperate forests or grasslands, and as a result, tropical deforestation releases relatively more greenhouse gases than the conversion of temperate forests or grasslands. Due to the diversity in the types of land that could be converted to agricultural production in the rest of the world and the uncertainty in predicting where this conversion may take place, as sensitivity analysis we consider the 95% confidence bounds on $\phi_{N,W}$ reported in the EPA (2010).

[31] The 30 year time frame is justified because this represents the average lifespan of an ethanol production facility. However, other studies have relied on different amortization assumptions. For example, Searchinger et al. (2008) use a 15 year time period.

[32] The EPA assessment of the RFS (EPA, 2010) also allows for cropland to expand onto pasture land. To the extent that the amount of land held as pasture falls in response to biofuel policy (due to reduced livestock production), this pathway of adjustment serves to mitigate the conversion of native ecosystems to agriculture, and therefore greenhouse gas emissions.

B.5 Intertemporal Dynamics

The numerical model generates a time path of economic outcomes at one year intervals between 2009 and 2015. To account for underlying dynamic trends that alter our emissions calculations, we allow for domestic and international income, average fuel economy, crop yields, average crude oil prices, and ethanol production technology to adjust exogenously.

We assume that household income grows at an annual rate of 1%. International income growth is modeled through increased world demand for US crop exports. Following historical average annual growth in crop exports over the years 2000-2009, we allow exports to grow by 1.13%, 2.70%, 0.21%, and 1.65% for corn, soybeans, wheat, and cotton, respectively.[33]

We allow fuel economy to exogenously increase by 0.22% per year. This trend is based on fuel economy projections from the 2002 National Research Council analysis of CAFE standards (Council, 2002) and vehicle fleet composition from (Bento et al., 2009).

The price of crude oil generally follows the Reference Scenario projections of AEO 2010, increasing monotonically from \$0.40 per liter (\$63.37 per barrel) in 2009 to \$0.47 per liter (\$73.85 per barrel) in 2015 (in constant 2003\$). Given the sharp spike in crude oil prices in 2008, followed by the precipitous decline in 2009, we take the average of the two prices as our 2009 crude oil price. To capture the strictly positive nature of crude prices in the AEO 2010, we linearly project crude oil prices between 2010 and 2012. For the years 2013 to 2015 we simply use the values taken directly from the AEO 2010 (adjusted to constant 2003\$). Note, in generating our counterfactual baseline this is the price path that we impose exogenously. However, when we simulate the impact of the RFS, the price of crude oil is allowed to endogenously adjust from this initial level, according to (B.2.9).

In 2009 baseline crop yields match observed average US yields taken from NASS. For the years 2010-2015, yields for all crops except hay follow 2010 USDA *Agricultural Projections to 2019*. Hay yields are allowed to increase by the average annual growth rate between the years 1990-2008, or 0.24% per year. CRP rental rates increase by 2% a year, matching historic trends reported in the CRPS. Improvements in international crop yields also follow 2010 Agricultural Projections.

We allow ethanol production technology to improve following US EPA projections (EPA, 2010). We allow the labor requirements of ethanol production to fall by roughly 50% between 2003 and 2015. These improvements are driven by increasing energy efficiency of ethanol production due to a projected expansion in efficient dry mill ethanol production (EPA, 2010). The corn-to-ethanol conversion ratio also improves. In 2015, the average ethanol conversion efficiency is 0.42 liters/kg, which is 6% higher than the 2003 value.

Projections for baseline total crude oil consumption in the rest of the world are from the International Energy Outlook (IEO) 2009 Reference Case. The IEO provides estimates for 2005 and 2006 and projections for 2010 and 2015. We linearly interpolate values of the years between the reported values. To calculate total petroleum consumption in the rest of the world we take the difference between world consumption and US consumption. The IEO projections do not break down total liquids consumed by type (gasoline, distillates, other). Therefore, we assume that the ratio of each petroleum type to total petroleum consumption is fixed at its 2003 value from 2003 to 2015. We calculate the 2003 shares using data from the

[33] Calculated using data from the USDA's Foreign Agricultural Service (FSA) *Production, Supply and Distribution Online* (PSD) dataset.

EIA's International Energy Statistics. This assumption is based on historic trends, which show that the shares of total crude consumption of each crude product are close to fixed. Between 2003 and 2007, the share of total crude consumption for any crude product changed by no more than 1% in the rest of the world.

B.6 Other US Biofuel Policies

RFS for Advanced Biofuels

The RFS for advanced biofuels expands from 2.3 billion liters in 2009 to 20.8 billion liters in 2015, and reaches a maximum of 79.5 billion liters by 2022. This mandate applies to any biofuel that achieves 50% lifecycle emissions savings or greater. Advanced biofuels span three dominant technologies: cellulosic ethanol, biomass based diesel, and sugarcane ethanol imported from Brazil and Caribbean Basin Initiative (CBI) countries. In the short-run (up to 2015), each technology faces challenges for expansion. This is in sharp contrast to corn ethanol and the corresponding RFS for conventional biofuels, which the EPA has determined can be met domestically given past production and plants currently being constructed/expanded (EPA, 2010). Of these three advanced technologies, biomass-based diesel currently has the largest share of US consumption by far, although it is a diesel substitute and in relative and absolute terms corresponds to a tiny share of the market for US transportation fuels.

The other two advanced biofuel technologies, cellulosic and imported sugarcane ethanol, are substitutes for gasoline, but so far have had even lower levels of penetration in the market for US transportation fuels. Cellulosic ethanol has its own aggressive sub-mandate within the RFS for Advanced biofuels, although EISA 2007 includes a "cellulosic loophole" which effectively allows the EPA to scale down the RFS for cellulosic biofuels if production is not there (see below). Since cellulosic ethanol continues to not be cost-effective relative to corn ethanol, producers have no incentive to expand production in the presence of this loophole. In the final rules for 2010, 2011, and 2012, the EPA has in fact exercised this legal authority, lowering the effective RFS for cellulosic biofuels *to* 7%, 3%, and 2%, respectively, of the statutory level stated in EISA 2007. Likewise, imports of ethanol to the US have averaged roughly 1 billion liters per year between 2006-2011, and are likely to remain at low volumes in the short-run.[34]

Given these trends, we think there are legitimate reasons to question whether the volumes for advanced biofuels specified under EISA 2007 will actually be achieved in the short run

[34] Data on ethanol imports is taken from the Renewable Fuels Association and does not distinguish between ethanol produced from corn and sugarcane. In all likelihood, almost all of this is sugarcane ethanol from Brazil and Caribbean Basin Initiative (CBI) countries. Sugarcane ethanol imports from Brazil and CBI countries face several challenges for expansion in the short-run which are discussed in detail in EPA (2010). Broadly these issues include: the presence of non-tariff trade barriers which continue to restrict the competitiveness of imports, limits to the rate at which production can be scaled up in Brazil and CBI, and the fact that ethanol imported from Brazil and CBI countries must first be converted from hydrous to anhydrous ethanol in order to be compatible with the US market and the rate at which dehydrating capacity can be scaled up is also limited. These issues affect long-term prospects as well, with the EPA analysis predicting a small role for ethanol imports from Brazil and CBI countries by 2022, accounting for only 8.4 billion liters of the 79.4 billion liter advanced RFS by 2022 (EPA, 2010).

and at volumes large enough to be of major economic consequence.[35] Given this, as well as the lack of credible data on feedstock production and technological conversion efficiency for advanced biofuels, we do not consider the RFS for advanced biofuels in our analysis.

The Cellulosic Loophole in EISA 2007

According to the federal law (specifically CAA section 211(o)(7)(D)(i)), as adjusted by EISA 2007, the "EPA is required to make a determination each year regarding whether the required volumes of cellulosic biofuel for the following year can be produced. For any calendar year for which the projected volume of cellulosic biofuel production is less than the minimum required volume, the projected volume becomes the basis for the cellulosic biofuel standard [our emphasis]. In such a case, the statute also indicates that EPA may also lower the required volumes for advanced biofuel and total renewable fuel (40 FR 14669 (2010-03-26))."

In effect, this "Cellulosic Loophole" allows the EPA administrator to revise the cellulosic mandates specified in EISA 2007 to the amount of cellulosic ethanol that is anticipated to be in production in the following year when specifying the annual Final Rules regarding the RFS. This loophole has been exercised repeatedly for all of the year's in which EISA 2007 has mandated significant quantities of cellulosic ethanol. In the 2010 Final Rule of the RFS, the EPA revised down the statutory requirement of 100 million gallons to a cellulosic mandate of 5.04 million gallons, or 93% lower than the amount specified under EISA 2007 (pg. 14718, 40 FR 14669 (2010-03-26)). The 2011 Final Rule, revised down the statutory requirement of 250 million gallons to a cellulosic mandate of 6.6 million gallons, or 97% lower than the statutory requirement (Table I.D.1, 40 FR 76790 (2010-12-09)). In the 2012 Final Rule, the EPA revised down the statutory requirement of 500 million gallons to a cellulosic mandate of 8.65 million gallons, or 98% lower than the statutory requirement (Table I.A.3-1, 40 FR 1320 (2012-01-09)).

Import Tariff

Historically, the other major federal biofuel policy in the US, along with the RFS and VEETC, was an import tariff of \$0.15/liter, which offset the VEETC for imported ethanol. The tariff was allowed to expire at the end of 2011, along with the VEETC. The expiration of the tariff should effectively have no impact on the demand for imported ethanol because the the VEETC expired concurrently. We abstract from ethanol imports in our framework, even after the expiration of the tariff, because US ethanol imports have historically been low and because of the short-run limitations to the expansion in sugarcane-based ethanol imports, as discussed above.

State-Level Policies

While the RFS and VEETC influence the total amount of ethanol used in the US, several states encourage biofuel adoption through state-level biofuel mandates. Likewise, in California biofuels can be used to comply with the Low Carbon Fuel Standard. An assortment of

[35] We are also suspicious regarding long-run (through 2022) prospects as well. After 2015, the RFS for cellulosic biofuels forms the bulk of the requirement for the RFS for advanced biofuels. Given limits in the EPA's ability to revise the bio-mass based diesel standard going forward, and the criticisms that would escalate if the EPA mandates large consumption of sugarcane ethanol from foreign sources, in all likelihood the EPA will have to revise the RFS for advanced biofuels in the future to reflect the adjustments it will need to make regarding the RFS for cellulosic biofuels.

ethanol production subsidies, loan guarantees, and tax credits are also prevalent at the state level.[36]

B.7 Model Validation

Comparison of Model Predictions to Historic Data

We calibrate the model to 2003 so we are able to compare our model's predictions against several years of observed data for which the RFS was largely considered to be non-binding. Table B.8 presents our out-of-sample model predictions averaged over the years 2004-2009 against observed data over that period.[37] Data for individual model years generally are similar to those reported here, with the caveat that, since we do not explicitly model commodity stocks in our model, our model predictions are smoother than those observed. Observed data is more variable, since various exogenous factors impact the amount of commodities stored or drawn down in a given year, such as droughts in individual commodity markets (for instance, wheat in 2007-2008), or interactions with other exogenous price swings elsewhere in the macroeconomy.

For corn, our model predictions are on average off by -1.78%, which suggests a good level of fit. Likewise, soybeans, wheat, and CRP predictions are off by similar margins. Hay exhibits slightly more error, at 5.88%, which likely reflects the fact that hay is the slack land-use in our model, but also because small deviations in observed hay yields magnify deviations relative to our model predictions. Cotton is off even more, with average deviations of -14.75%, although this is amplified by the fact that the base for cotton is orders of magnitude smaller than that for other crops. Our corn ethanol predictions are slightly higher, 8.62% greater, than that observed over this period, although in magnitude terms, we are off by slightly less than half a billion gallons for a given year.

Figure B.1 plots a two-year moving average of our measure of CRP land (General signup plus Continuous, Non-CREP signup) against the commodity price index for price received (pegged to 1990 -1992). Starting in 2007 and continuing through 2008, commodity prices started undergoing a considerable structural change. The commodity price index for prices received grew from a moving-average value of roughly 115 in 2006 to roughly 143 in 2008, denotes growth in average prices received of roughly 24%. By 2010 this sloughs off slightly to an index value of 136, which still denotes an increase in the average commodity price level relative to 2006 of roughly 19%. Not surprisingly, our measure of CRP starts to decline in 2008, resulting in a shedding of 2.33 million hectares between 2008 and 2010, given the data reported in Table B.10. Relative to the 2003 total, this is a reduction of 17.2%—a non-negligible reduction in CRP acres over this period.

For sake of comparison, our model finds a 0.2 million hectares or roughly half a million acre fall in CRP due to the RFS in 2012 when the VEETC is continued (see Table B.10). This is internally consistent with the CRP acreage elasticity of -0.07 (as reported in Table 2.1, given the change in the returns to cropland arising due to the change in the RFS. In this year our model predicts the RFS will bind by 6.1 billion liters (see Table 2.2), requiring an additional 1.1 million hectares of corn land devoted to ethanol production (see Table B.10).

[36]For a complete list of state level biofuel policies see the US Department of Energy's Alternative Fuels & Advanced Vehicles Data Center (http://www.afdc.energy.gov/afdc/laws/state).

[37]Data for individual model years are available from the authors by request.

This implies a fall in CRP acres of 0.03 hectares for every 1,000 liters of ethanol added by the RFS, relative to an increase in corn hectares devoted to ethanol production of 0.18 hectares per 1,000 liters. We believe our model's prediction for this fall in CRP is conservative and reasonable. Further, it is fully consistent with observed changes in CRP acreages reported in recent years. Between 2008 and 2009 corn ethanol expanded by 2.4 billion liters and corn acreage expanded by 0.28 million hectares, whereas CRP acreage fell by 0.38 million hectares.

Comparison of Model Predictions to 2006-2009 Average of USDA Long-Term Projections

Table B.9 compares our model predictions against an average of the USDA's Long-Term Projections for the years 2006, 2007, 2008, and 2009. We compare vis-a-vis an average of Long-Term Projections, given the large degree of variation in the projections over this time period, owing to the considerable changes in commodity markets observed in these years and changes in the assumptions underlying the USDA estimates, in particular prior to the EISA 2007 being fully embedded into their projections.[38] In general, our estimates are largely consistent with the USDA Long-Term Projections.

B.8 Additional Sensitivity Analysis

In light of research suggesting that the efficiency and lifecycle emissions of ethanol production is rapidly improving (Liska et al., 2009), we conducted sensitivity analysis on the energy and corn requirements of ethanol production (Table B.18). Lowering the energy requirements of ethanol production reduces the net change in emissions due to the RFS by increasing intended emissions savings per liter of ethanol added, but has a negligible impact on land and fuel market leakage. Reducing the corn requirements of ethanol production increases intended emissions savings and increases the quantity of ethanol in the baseline, and therefore reduces the quantity of ethanol added by the RFS. In our results, the large differences in the baseline level of ethanol and the resulting land market adjustments mask two additional impacts of lowering the corn required for ethanol production. First, the RFS will have smaller impacts on land markets, therefore lowering land market leakage. Second the price of ethanol, and therefore the price of blended fuel will be less responsive to increases in the price of corn and domestic fuel market leakage will be larger.

B.9 Additional Results

Table B.12 presents the impact of the RFS on the prices of crops. Table B.13 presents the total change in emissions, intended emissions savings and each primary source of leakage per unit of ethanol added by the RFS. Tables B.16 and B.17 replicates the sensitivity analysis presented in the text for the year 2012. Table B.18 reports emissions results under varying assumptions regarding the efficiency of ethanol production for the year 2015.

[38]Hay and CRP are not reported here since the USDA Long-Term Projections do not include projections for hay or land held in the CRP.

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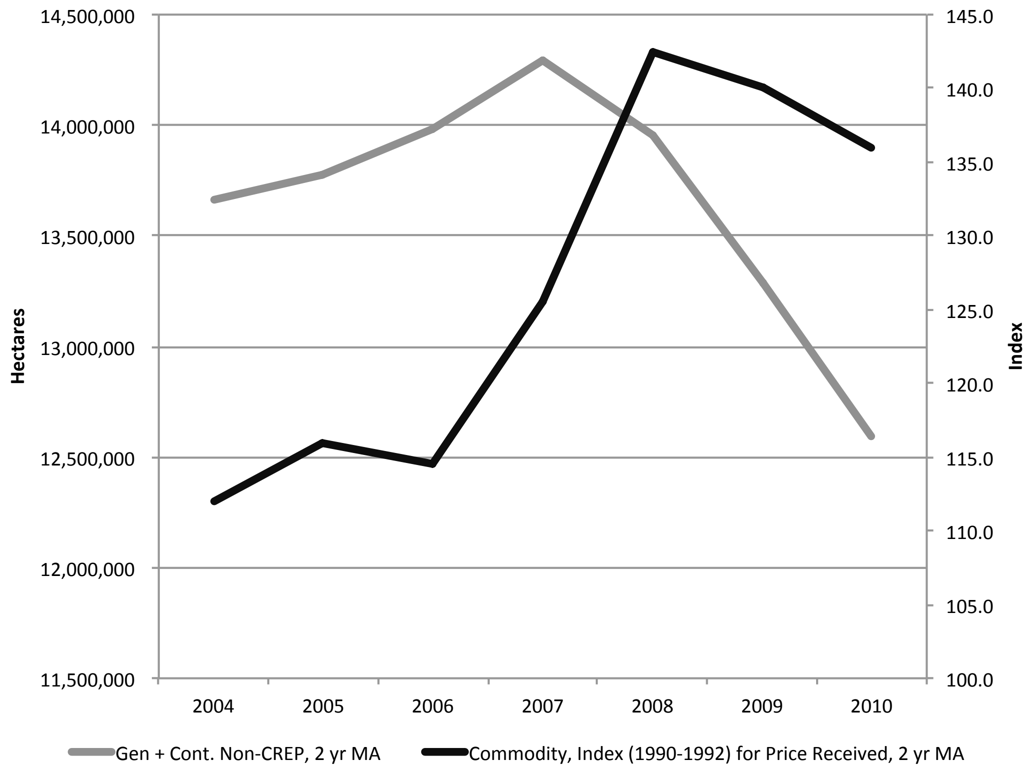

Figure B.1: CRP Acres Against Commodity Price Index (Price Received)

Table B.1: Description of US Economy in Year of Calibration - 2003

	Value	Source
Total Size of Economy (billion $)	$7,667.60	NIPA
Net Government Expenditures (billion $)	$2,828.90	NIPA
After Tax Value of Labor (billion $)	$4,811.08	
Net Returns from Land Endowment (billion $)	$27.61	NASS, CRPS, CCR
US Land Endowment (million hectares)	112.68	
Corn	31.37	NASS
Soybeans	29.33	NASS
Wheat	21.47	NASS
Hay	25.65	NASS
Cotton	4.68	NASS
CRP	13.57	CRPS
Crop Yields (metric ton/hectare)		
Corn	8.9	NASS
Soybeans	2.6	NASS
Wheat	3.0	NASS
Hay	6.1	NASS
Cotton	0.8	NASS
Crop Prices ($/metric ton)		
Corn	$95.23	NASS
Soybeans	$269.62	NASS
Hay	$94.22	NASS
Wheat	$118.65	NASS
Cotton	$1,036.32	NASS
Fuel Quantities		
VMT (trillion passenger miles)	2.69	FHWA
Blended Fuel (billion liters)	497.21	
Ethanol (billion liters)	10.39	FHWA
Regular Gasoline (billion liters)	490.28	FHWA
Domestic Crude Oil (billion barrels)	2.34	GCH, CSD, BNI
Fuel Prices		
VMT ($/passenger mile)	$0.19	
Blended Fuel ($/liter)	$0.41	
Ethanol ($/liter)	$0.35	
Regular Gasoline ($/liter)	$0.23	AER
Crude Oil ($/liter)	$0.18	AER
Labor Tax Rate (%)	36.59%	
Fuel Tax ($/liter)	$0.10	FHWA
CRP Rental Payment ($/hectare)	$114.48	CRPS
Price of Labor ($/hour)	$9.05	NASS

Notes: Entries with no source listed are imputed given other data and calibration assumptions.

Table B.2: Key Parameter Values

Parameter	Value	Source
Households		
Elasticity of substitution, Household Utility, σ_U	0.5	See Text
Elasticity of substitution, Household Utility, σ_T	0.09	See Text
Elasticity of substitution, VMT, σ_M	0.21	See Text
Ratio of fuel cost to total cost of driving	0.4	See Text
Initial Fuel Economy (km/liter)	8.7	FHWA
Ethanol		
kilograms corn required per liter ethanol, λ_{E,Y_1}	2.56	(Wang, 2009)
Labor expenditures per liter ethanol	\$0.13	(Farrell et al., 2006)
Regular Gasoline and Crude Oil		
Elasticity of substitution, Regular Gasoline Production, σ_P	0.06	See Text
Share of per unit crude oil cost to total cost of gasoline	0.61	GCH, CSD, BNI
Own price elasticity of crude oil supply	0.50	See Text
Crude oil yield for regular gasoline	0.47	GCH, CSD, BNI

Notes: See text for acronym definitions. Values are reported for 2003. A subset of parameters are updated annually, see text for details.

Table B.3: Targeted Crop Area Elasticities

	Corn Area	Soybean Area	Hay Area	Wheat Area	Cotton Area
Corn Price	0.29	-0.23	-0.05	-0.05	-0.07
Soybean Price	-0.15	0.27	-0.01	-0.01	-0.08
Hay Price	-0.07	-0.01	0.20	-0.08	-0.10
Wheat Price	-0.07	-0.01	-0.06	0.34	-0.06
Cotton Price	-0.03	-0.02	-0.08	-0.01	0.47

Notes: The elasticity of CRP land with respect to the marginal net returns to cropland is -0.07. The own price elasticity of hay area, the cross price elasticity of hay area with respect to the price of corn and the elasticity of corn area with respect to the price of hay represent an average of Arnade and Kelch (2007) and Orazem and Miranowski (1994). The elasticity of hay area with respect to the price soybeans, wheat and cotton, and the elasticity of wheat and cotton area with respect to the price of hay represent best guesses. All remaining values are from Lin et al. (2000).

Table B.4: Agricultural Expenditure Dataset

Total Expenditures ($/hectare)

	Labor	Capital	Energy	Fertilizer	Total
Corn	73.32	142.06	57.06	386.97	659.41
Soybeans	44.50	108.33	21.67	209.92	384.43
Hay	49.08	130.13	27.06	153.26	359.52
Wheat	49.08	130.13	27.06	167.96	374.22
Cotton	124.39	157.14	60.27	749.58	1092.37

Components of Fertilizer Expenditure ($/hectare)

	N	P	K	Seed	Chemicals	Other
Corn	89.97	21.40	19.05	84.76	64.74	107.05
Soybeans	2.52	5.41	7.78	67.76	41.81	84.63
Hay	20.11	15.20	7.69	18.78	17.15	74.31
Wheat	43.89	11.27	2.59	18.78	17.15	74.31
Cotton	52.19	13.57	13.49	91.90	162.62	415.83

Table B.5: Additional Calibration Parameters

Model Parameter	Value	Source
Households		
Expenditure Share on Food	0.035	
Expenditure Share on VMT	0.065	
Crop Export Markets		
Elasticity of ROW demand for US corn exports	-0.65	
Share of corn exports to Total US Production	0.19	PSD
Elasticity of ROW demand for US soybean exports	-0.6	
Share of soybean exports to Total US Production	0.36	PSD
Elasticity of ROW demand for US wheat exports	-0.55	
Share of wheat exports to Total US Production	0.49	PSD
Elasticity of ROW demand for US cotton exports	-0.75	
Share of cotton exports to Total US Production	1	PSD
Ethanol		
Average tariff rate (plus fuel surcharge) per liter of ethanol	\$0.02	
Gasoline and Crude Oil		
Share of crude oil cost to total cost of gasoline per liter	0.61	EIA
Crude oil yield for gasoline	0.47	EIA
Other Markets		
Elasticity of substitution, Food Production, σ_{X1}	0.08	
Elasticity of substitution, Food Production, σ_{X2}	0.3	
Elasticity of substitution, Food Production, σ_{X3}	0.25	
Share of crop expenditures on food to total food expenditures	0.19	

Table B.6: Calibration of Crude Oil Market

Crude Market Component	Quantity (billion liters)	Ratio with Crude for US Gasoline	Central Elasticity
Total World Crude Oil	4545.8	-	-
US Demand for Crude Oil for Gasoline	490.3	-	0.50
US Crude Oil Supply	499.6	1.0	0.045
ROW Crude Oil Supply	4046.2	8.3	0.035
ROW Crude Oil Demand	3419.5	7.0	-0.02
US Distillate Demand	225.0	0.5	-0.02
US Other Crude Products Demand	411.0	0.8	-0.02

Notes: The value for crude for US gasoline is the value used in our model. This value is slightly below the total quantity of crude for US gasoline reported by the EIA because we ignore US gasoline for non-transportation purposes in our model. The elasticity of crude for US gasoline is calculated following equation (B.3.2). All other elasticity values are from literature sources reported in the text. Our category of other crude products includes residual fuels, jet fuel, kerosene, LPG and EIA defined other petroleum products.

Table B.7: Final Product/Activity Emissions Factors

	Central	Low	High	Source
Gasoline ($kgCO_2e$/liter)	3.0			
Combustion	2.4	-	-	EPA (2010)
Production	0.6	-	-	EPA (2010)
Ethanol ($kgCO_2e$/liter)				
Combustion	0.02	-	-	EPA (2010)
Production	0.6	-	-	EPA (2010)
Crude Oil ($kgCO_2e$/liter)	2.6	-	-	EPA (2011)
Agriculture ($mgCO_2e$/ha/year)				
Corn	3.2	2.9	5.6	
Soybeans	0.5	1.8	0.4	
Hay	1.3	1.3	2.5	
Wheat	1.0	1.6	1.3	
Cotton	1.4	1.6	2.9	
Land Use Emissions Benefits Lost Upon Conversion ($mgCO_2e$/ha/year)				
CRP	2.3	1.1	4.6	Fargione et al. (2008)
Rest of World	8.0	5.9	10.5	EPA (2010)

Notes: See Appendix for description of calculations. N_2O emissions from agricultural production depend on crop yields and therefore vary by year and policy. Values in baseline for 2003 are reported here. The emissions factor for crude oil is the average emissions from gasoline and distillates used outside the US, weighted by 2003 quantities of these products.

Table B.8: Comparison of Out of Sample Model Predictions to Historic Data

	2003	2004-2009, Avg.
Land Harvested (million hectares)		
Corn, Our Prediction	31.38	33.14
Corn, USDA	31.38	33.74
% Difference	0.00%	-1.78%
Soybeans, Our Prediction	29.33	29.18
Soybeans, USDA	29.33	29.34
% Difference	0.00%	-0.56%
Hay, Our Prediction	25.65	26.07
Hay, USDA	25.64	24.63
% Difference	0.02%	5.88%
Wheat, Our Prediction	21.47	20.69
Wheat, USDA	21.47	20.46
% Difference	0.00%	1.08 %
Cotton, Our Prediction	4.86	3.76
Cotton, USDA	4.86	4.41
% Difference	-0.01%	-14.75%
CRP, Our Prediction	13.57	13.41
CRP, USDA	13.57	13.61
% Difference	0.00%	-1.50%
Ethanol Quantities (billion liters)		
Ethanol Baseline Quantities	10.4	27.6
Total US Demand, RFA	10.4	25.4
% Difference	0.00%	8.62%

Notes: USDA value for corn includes total harvested for silage and for grain.

Table B.9: Comparison of Out of Sample Model Predictions to Average of 2006-2009 USDA Long-Term Projections

	2010	2012	2015
Harvested Land (million hectares)			
Corn Acres, Our Baseline Estimate	33.86	33.90	33.38
Corn Acres, Our Post-RFS Estimate	34.27	34.98	35.33
Corn Acres, Avg. 2006-2009 LT Proj.*	32.67	33.18	33.07
% Difference, Baseline	3.65%	2.18%	0.93%
% Difference, Post-RFS	4.91%	5.45%	6.83%
Soybean Acres, Our Baseline Estimate	29.08	29.38	29.44
Soybean Acres, Our Post-RFS Estimate	28.97	29.05	28.87
Soybean Acres, Avg. 2006-2009 LT Proj.	28.37	28.00	27.75
% Difference, Baseline	2.51%	4.94%	6.10%
% Difference, Post-RFS	2.13%	3.77%	4.04%
Wheat Acres, Our Baseline Estimate	20.70	20.57	22.44
Wheat Acres, Our Post-RFS Estimate	20.62	20.30	22.08
Wheat Acres, Avg. 2006-2009 LT Proj.	20.35	20.17	20.03
% Difference, Baseline	1.74%	1.97%	12.02%
% Difference, Post-RFS	1.34%	0.61%	10.23%
Cotton Acres, Our Baseline Estimate	3.75	3.72	3.77
Cotton Acres, Our Post-RFS Estimate	3.69	3.57	3.48
Cotton Acres, Avg. 2006-2009 LT Proj.	4.40	4.51	4.56
% Difference, Baseline	-14.86%	-17.61%	-17.37%
% Difference, Post-RFS	-16.23%	-21.00%	-23.83%

Ethanol (billion liters)			
Ethanol, Our Baseline Estimate	41.79	43.94	45.44
Ethanol, Avg. 2006-2009 LT Proj.**	38.31	40.47	43.23
% Difference	-8.29%	-7.92%	4.94%

Notes: *: Does not include corn land harvested for silage, since silage is not tracked by USDA L-T Projections. **: Figure for 2012 and 2015 takes corn for ethanol and converts to ethanol using conversion parameters from our model for the given year. Figure for 2009 comes from the RFA and represents total US demand for ethanol. ***: Estimate computed is based on a per gallon of blended fuel share mandate on ethanol consumption, which is calculated annually by taking the RFV statutory quantities and dividing by the expected blended fuel consumption (post-policy) for a given year.

Table B.10: Change in CRP For Years 2003-2010 (Million hectares)

Year	General	Cont. Non-CREP	Total	Annual Change	% Annual Change
2003	12.80	0.77	13.57		
2004	12.88	0.88	13.76	0.19	1.43%
2005	12.84	0.96	13.80	0.04	0.28%
2006	13.13	1.04	14.17	0.37	2.70%
2007	13.32	1.10	14.42	0.25	1.78%
2008	12.36	1.12	13.48	-0.94	-6.52%
2009	11.90	1.20	13.10	-0.38	-2.84%
2010	10.79	1.30	12.09	-1.01	-7.73%

Notes: Data taken from *Conservation Reserve Program Annual Summary and Enrollment Statistics* for years 2003 through 2010.

Table B.11: Alternative Calculations of Leakage from World Crude Oil Market, 2015

	2012	2015
RFS (VEETC Renewed)		
ROW Crude Baseline (billion liters)	4513.0	4667.4
ROW Crude Change (billion liters)	1.5	2.9
Change in US Distillates	0.1	0.1
Change in US Other	0.1	0.3
Change in ROW Gasoline	0.3	0.5
Change in ROW Distillates	0.4	0.7
Change in ROW Other	0.6	1.3
Leakage from world crude market ($TgCO_2e$)		
Gasoline Only	0.6	1.2
Gasoline and Distillates	1.8	3.6
All Crude Products	3.4	6.7
Net Change in Emissions (TgCO2e)		
Gasoline Only	0.4	2.1
Gasoline and Distillates	1.6	4.5
All Crude Products	3.2	7.6
RFS (VEETC Swapped)		
ROW Crude Baseline (billion liters)	4513.0	4667.4
ROW Crude Change (billion liters)	2.4	3.9
Change in US Distillates	0.1	0.2
Change in US Other	0.2	0.3
Change in ROW Gasoline	0.4	0.7
Change in ROW Distillates	0.6	1.0
Change in ROW Other	1.0	1.7
Leakage from world crude market ($TgCO_2e$)		
Gasoline Only	1.0	1.6
Gasoline and Distillates	2.9	4.8
All Crude Products	5.5	9.0
Net Change in Emissions ($TgCO_2e$)		
Gasoline Only	-6.5	-5.2
Gasoline and Distillates	-4.6	-2.0
All Crude Products	-2.0	2.2

Notes: Our category of other crude products includes residual fuels, jet fuel, kerosene, LPG and EIA defined other petroleum products.

Table B.12: Impact of RFS on Crop Prices

	2012	2015
RFS (VEETC Renewed)		
Baseline Corn Price($/metric ton)	126.2	136.7
Change in Corn Price	12.6%	25.3%
Baseline Soybean Price ($/metric ton)	300.1	331.8
Change in Soybean Price	0.7%	3.0%
Baseline Hay Price ($/metric ton)	127.6	194.4
Change in Hay Price	5.9%	10.3%
Baseline Wheat Price ($/metric ton)	160.2	133.8
Change in Wheat Price	5.6%	20.0%
RFS (VEETC Swapped)		
Baseline Corn Price($/metric ton)	126.2	136.7
Change in Corn Price	12.1%	24.6%
Baseline Soybean Price ($/metric ton)	300.1	331.8
Change in Soybean Price	0.7%	2.9%
Baseline Hay Price ($/metric ton)	127.6	194.4
Change in Hay Price	5.9%	10.2%
Baseline Wheat Price ($/metric ton)	160.2	133.8
Change in Wheat Price	5.5%	19.8%

Table B.13: Leakage per Unit Added Ethanol

	2010	2012	2015
RFS (VEETC Renewed)			
Net Change in Emissions (kgCO_2e/liter)	0.10	0.27	0.40
Intended Emissions Savings, I	0.82	0.83	0.85
Net Leakage	0.91	1.09	1.25
Land Market Leakage	0.34	0.58	0.72
From the Domestic Land Market, L^{DA}	-0.25	-0.08	-0.07
From the World Land Market, L^{WA}	0.59	0.66	0.79
Fuel Market Leakage	0.57	0.51	0.53
From the Domestic Fuel Market, L^{DF}	0.30	0.22	0.22
From the World Crude Oil Market, L^{WF}	0.27	0.29	0.31
RFS (VEETC Swapped)			
Net Change in Emissions (kgCO_2e/liter)	-1.57	-0.79	-0.18
Intended Emissions Savings, I	0.82	0.83	0.85
Net Leakage	-0.75	-0.04	0.67
Land Market Leakage	0.34	0.59	0.73
From the Domestic Land Market, L^{DA}	-0.26	-0.08	-0.07
From the World Land Market, L^{WA}	0.60	0.67	0.80
Fuel Market Leakage	-1.09	-0.55	-0.06
From the Domestic Fuel Market, L^{DF}	-1.68	-1.05	-0.49
From the World Crude Oil Market, L^{WF}	0.59	0.50	0.43

Table B.14: Impact of RFS on Land and Fuel Markets Relative to No-VEETC Baseline

	2010	2012	2015
Ethanol Baseline, No VEETC (billion liters)	22.7	24.5	31.2
Change in Ethanol due to RFS	23.0	25.8	25.8
Domestic Corn Baseline (million ha)	30.5	31.0	31.7
Additional Corn Required	4.1	4.4	4.3
Change in Domestic Corn	3.8	4.4	3.6
From Other Crops	-2.6	-3.3	-2.9
From Land held in CRP	-1.0	-1.2	-0.8
Change in World Non-Agricultural Land	-1.7	-2.0	-2.3
Baseline Blended Fuel Price ($/liter)	0.6	0.6	0.7
Change in Price of Blended Fuel	-1.9%	-1.7%	-1.3%
Baseline Ethanol Price ($/liter)	0.3	0.3	0.3
Change in Price of Ethanol	20.9%	32.1%	39.9%
Baseline Gasoline Price ($/liter)	0.4	0.4	0.5
Change in Price of Gasoline	-4.5%	-5.2%	-5.5%
Baseline Blended Fuel (billion liters)	462.8	470.0	468.7
Change in Blended Fuel	3.3	3.1	2.7
Baseline Crude Oil Price ($/liter)	0.4	0.5	0.5
Change in Crude Oil Price	-5.8%	-6.6%	-6.9%
Baseline World Crude Oil (billion liters)	2083.0	2163.8	2217.9
Change in World Crude Oil	2.4	2.8	3.1

Table B.15: Leakage per Unit Added Ethanol Relative to No-VEETC Baseline

	2010	2012	2015
Net Change in Emissions (kgCO2e/liter), $dGHG$	0.30	0.27	0.26
Intended Savings, I	0.84	0.86	0.87
Total Leakage	1.14	1.13	1.13
Total Land Market Leakage	0.54	0.54	0.55
Leakage in Domestic Land Market	-0.05	-0.07	-0.16
Leakage from World Land Market	0.60	0.61	0.71
Total Fuel Market Leakage	0.59	0.59	0.58
from domestic fuel market	0.32	0.30	0.27
from world crude market	0.27	0.29	0.31

Table B.16: Emissions in 2012 Under Alternative Parameter Assumptions, Fuel Markets

Crude Oil Excess Supply Elasticity Fuel and VMT Elasticity of Demand	Central Central	Low Central	High Central	Central Low	Central High
RFS (VEETC Renewed)					
Baseline Ethanol Consumption (billion liters)	43.9	45.4	43.2	44.9	42.9
Change in Ethanol Consumption	6.1	4.6	6.8	5.0	7.1
Net Change in Emissions (kgCO_2e per liter ethanol added)	0.27	0.58	0.12	0.19	0.34
Intended Savings, I	0.83	0.83	0.83	0.83	0.83
Domestic Land Market Leakage, L^{DA}	-0.08	-0.10	-0.07	-0.08	-0.07
World Land Market Leakage , L^{WA}	0.66	0.68	0.65	0.68	0.65
Domestic Fuel Market Leakage, L^{DF}	0.22	0.59	0.05	0.12	0.30
World Fuel Market Leakage, L^{WF}	0.29	0.24	0.32	0.30	0.29
RFS (VEETC Swapped)					
Baseline Ethanol Consumption (billion liters)	43.9	45.4	43.2	44.9	42.9
Change in Ethanol Consumption	5.8	4.4	6.5	4.9	6.8
Net Change in Emissions (kgCO_2e per liter ethanol added)	-0.79	-0.51	-0.92	-0.73	-0.82
Intended Savings, I	0.83	0.83	0.83	0.83	0.83
Domestic Land Market Leakage, L^{DA}	-0.08	-0.09	-0.07	-0.08	-0.07
World Land Market Leakage , L^{WA}	0.67	0.69	0.66	0.68	0.66
Domestic Fuel Market Leakage, L^{DF}	-1.05	-0.73	-1.21	-0.98	-1.10
World Fuel Market Leakage, L^{WF}	0.50	0.45	0.53	0.48	0.52

Notes: Elasticity of crude oil excess supply is 0.25, 0.5 and 0.75 in the low, central and high cases respectively. The elasticity of world crude oil demand is -0.01, -0.02 and -0.03 in the low, central and high cases respectively. Fuel and VMT elasticities of demand are varied by jointly modifying the elasticities of substitution, σ_U, σ_W, and σ_M in equations (B.2.1). The high case increases the elasticities of blended fuel and VMT demand by 0.1 from their central values whereas the low case considers a joint decrease in both elasticities by 0.1.

Table B.17: Emissions in 2012 Under Alternative Parameter Assumptions, Land Markets

Elasticities of Crop Demand for Food Production Agriculture and Land Use Emissions	Central Central	Low Central	High Central	Central Low	Central High
RFS (VEETC Renewed)					
Baseline Ethanol Consumption (billion liters)	43.9	41.9	47.3	43.9	43.9
Change in Ethanol Consumption	6.1	8.1	2.6	6.1	6.1
Net Change in Emissions (kgCO_2e per liter ethanol added)	0.27	0.36	0.12	-0.18	1.11
Intended Savings, I	0.83	0.83	0.83	0.88	0.38
Domestic Land Market Leakage, L^{DA}	-0.08	0.02	-0.22	-0.20	-0.05
World Land Market Leakage , L^{WA}	0.66	0.70	0.62	0.39	1.04
Domestic Fuel Market Leakage, L^{DF}	0.22	0.17	0.26	0.22	0.22
World Fuel Market Leakage, L^{WF}	0.29	0.30	0.29	0.29	0.29
RFS (VEETC Swapped)					
Baseline Ethanol Consumption (billion liters)	43.9	41.9	47.3	43.9	43.9
Change in Ethanol Consumption	5.8	7.8	2.3	5.8	5.8
Net Change in Emissions (kgCO_2e per liter ethanol added)	-0.79	-0.43	-2.51	-1.23	0.07
Intended Savings, I	0.83	0.83	0.83	0.88	0.38
Domestic Land Market Leakage, L^{DA}	-0.08	0.02	-0.22	-0.20	-0.05
World Land Market Leakage , L^{WA}	0.67	0.70	0.65	0.39	1.05
Domestic Fuel Market Leakage, L^{DF}	-1.05	-0.78	-2.94	-1.05	-1.05
World Fuel Market Leakage, L^{WF}	0.50	0.46	0.82	0.50	0.50

Notes: The low and high cases for the elasticity of crop demand for food production are constructed by doubling and halving the elasticities of substitution in equation (B.2.10). Low agriculture and land use emissions case sets all emissions factors to low values, and lowers the world land use conversion ratios by 20%. High agriculture and land use emissions case sets all emissions factors to high values and increases the world land use conversion ratios by 20%.

Table B.18: Emissions in 2015 Under Alternative Ethanol Production Assumptions

Corn Required for Ethanol Production Energy Required for Ethanol Production	Central Central	Central Low	Central High	Low Central	High Central	Low Low	High High
RFS (VEETC Renewed)							
Baseline Ethanol Consumption (billion liters)	45.4	46.5	44.3	51.3	40.3	52.4	39.2
Change in Ethanol Consumption	11.4	10.3	12.6	5.5	16.6	4.4	17.6
Net Change in Emissions (kgCO_2e per liter ethanol added)	0.40	0.37	0.42	0.61	0.36	0.72	0.40
Intended Savings, I	0.85	0.91	0.80	0.88	0.82	0.94	0.76
Domestic Land Market Leakage, L^{DA}	-0.07	-0.05	-0.09	0.01	-0.10	0.07	-0.11
World Land Market Leakage , L^{WA}	0.79	0.80	0.78	0.90	0.80	0.99	0.79
Domestic Fuel Market Leakage, L^{DF}	0.22	0.22	0.22	0.28	0.15	0.30	0.16
World Fuel Market Leakage, L^{WF}	0.31	0.31	0.31	0.30	0.32	0.30	0.32
RFS (VEETC Swapped)							
Baseline Ethanol Consumption (billion liters)	45.4	46.5	44.3	51.3	40.3	52.4	39.2
Change in Ethanol Consumption	11.1	10.0	12.2	5.2	16.2	4.1	17.3
Net Change in Emissions (kgCO_2e per liter ethanol added)	-0.18	-0.26	-0.10	-0.60	-0.04	-0.80	0.03
Intended Savings, I	0.85	0.91	0.80	0.88	0.82	0.94	0.76
Domestic Land Market Leakage, L^{DA}	-0.07	-0.05	-0.09	0.02	-0.10	0.09	-0.11
World Land Market Leakage , L^{WA}	0.80	0.81	0.79	0.93	0.80	1.04	0.80
Domestic Fuel Market Leakage, L^{DF}	-0.49	-0.56	-0.42	-1.22	-0.33	-1.62	-0.30
World Fuel Market Leakage, L^{WF}	0.43	0.44	0.42	0.56	0.40	0.63	0.40

Notes: Corn for ethanol production analysis varies $\lambda_{E,Y}$ in equation (B.2.6). Low case assumes that 5% less corn is required per liter than central case in 2015. High case assumes that there is no improvement in corn required per unit ethanol between 2003 and 2015. Energy required for ethanol production analysis varies $\lambda_{E,L}$ in equation (B.2.6) and the emissions factor ϕ_E. The sensitivity cases adjust labor that is required per liter ethanol of the central case in 2015 to reflect a 10% increase and decrease in energy use. ϕ_E is scaled proportionally to this change in energy use.

Appendix C

Appendix to On the Trade-Offs of Regulating Multiple Unpriced Externalities with a Single Instrument: Evidence from Biofuel Policies

This appendix provides the intermediate steps in the derivation of the marginal welfare formula and a full exposition of the simulation model and additional results. Section C.1 derives the marginal welfare formula reported in (3.3.24). Section C.2 provides additional details regarding biofuel support programs. In Section C.3 we present the functional forms used in the simulation model and highlight the key differences between the analytical simulation versions of the model. Section C.4 discusses the parameter values and data sources used to calibrate the simulation model. In Section C.4.1 we outline the assumptions regarding the dynamic trends that underlie our simulation results. Section C.5 validates our baseline against historical data and compares our projections to the USDA's *Long Term Projections*. Section C.6 discusses how greenhouse gas emissions are calculated in the model and the parameters and coefficients used to calculate then. Section C.7 provides details on the change in the trade balance calculations. Section C.8 provides additional discussion regarding the assumptions and data sources used to calculate marginal external damages and benefits. In Section C.9 we provide additional details on the calculations underlying Section 3.4.10 in the main text. Finally, Section C.10 contains tabular results for the impact of the RFS on crop prices, as well as additional sensitivity results.

C.1 Derivation of the Marginal Welfare Formula

Welfare in the model is the sum of two components, welfare from domestic consumption and production and welfare due to the fact that a portion of production and consumption in the domestic economy is delivered to/received from export/import markets in the rest of the world. That is:

$$V(\theta, G, K, T, D, J, Z) = V^D(\theta, G, K, T, D, J, Z) + V^W(\theta, G), \tag{C.1.1}$$

where $V^D(\theta, G, K, T, D, J, Z)$ is welfare from domestic consumption and production and $V^W(\theta, G)$ is welfare owing to the fact that a portion of production and consumption results due to export/import markets with the rest of the world.

We note that $V^W(\theta, G)$ is given by the sum of the changes in consumer surpluses in the excess demand functions for corn and non-corn agricultural products less the change in producer surplus given the excess supply function for crude oil. That is:

$$\begin{aligned} V^W(\theta, G) = \lambda_1 \Bigg[& \int_{p_0^Y}^{p_{RFS}^Y} Y^{X,W}(p^Y) dp^Y + \int_{p_0^Z}^{p_{RFS}^Z} Z^{X,W}(p^Y, p^Z) dp^Z \\ & - \int_{p_0^R}^{p_{RFS}^R} R^W(p^R) dp^R \Bigg], \end{aligned} \tag{C.1.2}$$

where p_0^Y, p_0^Z, and p_0^R are the baseline prices of corn, non-corn, and crude oil, and p_{RFS}^Y, p_{RFS}^Z, and p_{RFS}^R are the prices after the RFS is imposed, that is, given a binding value of θ. Since these are equilibrium prices these are functions of θ and G. λ_1 is the marginal change in utility from a marginal change in income given by the solution to $V^D(\theta, G, K, T, D, J, Z)$ below. This simply keeps utility in consistent terms as the term in square brackets in (C.1.2) is in dollars (money-metric utility), whereas $V^D(\theta, G, K, T, D, J, Z)$ is an ordinal measure of utility. Multiplying $V^W(\theta, G)$ by λ_1, thus simply allows us to report utility in units consistent with $V^D(\theta, G, K, T, D, J, Z)$.

Total differentiation of (C.1.2) with respect to θ, after applying the fundamental theorem of Calculus and normalizing the result by $-\frac{1}{\lambda_1}$, provides:

$$\left(-\frac{1}{\lambda_1}\right)\left(\frac{dV^W}{d\theta}\right) = \left[R^W\left(\frac{dp^R}{d\theta}\right) - Y^{X,W}\left(\frac{dp^Y}{d\theta}\right) - Z^{X,W}\left(\frac{dp^Z}{d\theta}\right)\right], \tag{C.1.3}$$

which is the change in the trade balance term, dW^{B}, reported in (3.3.24).

We next turn to the derivation of the change in welfare from the component of welfare that arises from domestic consumption and production, $\left(-\frac{1}{\lambda_1}\right)\left(\frac{dV^D}{d\theta}\right)$, which summing together with the term in (C.1.3), provides the full expression for (3.3.24). Maximizing (3.3.1), subject to (3.3.2), (3.3.3), (3.3.4), (3.3.6), and (3.3.7), we have:

$$\begin{aligned} & V^D(\theta, G, K, T, D, J, Z) \\ & \quad = \max_{X,C,M,E,P,L^H} u\left(M, C, X\right) + \xi(K) - \nu(T) - \psi(D) - \kappa(J) - \mu(Z) \\ & \quad + \lambda_1 \Big[\left(1 - t_L\right) \left(\bar{L} - \tau M\right) + G + \pi^{\bar{A}} - w^X X - C - \left(w^E - s^E\right) E - w^P P \\ & \quad - t^F F\left(E, P\right) - L^H \Big] \\ & \quad + \lambda_2 \left[M\left(F\left(E, P\right), L^H\right) - M\right] \\ & \quad + \lambda_3 \left[\theta F\left(E, P\right) - E\right]. \end{aligned} \tag{C.1.4}$$

Note that we suppress as arguments in $V(\cdot)$ those policy parameters that remain constant throughout our simulations, e.g. s^E, s^N, t^F, and t^L. Since π^A, w^X, w^E, and w^P are a function of final prices, which are themselves a function of the endogenous policy vector (θ, G), we also omit them. Thus, indirect utility is a function of the endogenous policy vector, (θ, G), and the vector of aggregate externalities in the economy, K, T, D, J and Z. The first-order conditions to (C.1.4) are given by:

$$\begin{aligned} C &: \frac{u_C}{\lambda_1} = 1 \\ X &: \frac{u_X}{\lambda_1} = w^X \\ M &: \frac{u_M}{\lambda_1} = \frac{\lambda_2}{\lambda_1} + \tau\left(1 - t_L\right) \\ E &: \frac{\lambda_2}{\lambda_1} M_F F_E + \frac{\lambda_3}{\lambda_1}\left(\theta F_E - 1\right) = w^E - s^E + t^F F_E \\ P &: \frac{\lambda_2}{\lambda_1} M_F F_P + \frac{\lambda_3}{\lambda_1}\theta F_P = w^P + t^F F_P \\ L_H &: \frac{\lambda_2}{\lambda_1} M_H = 1 \end{aligned} \tag{C.1.5}$$

Solving the equations for E and P for $\frac{\lambda_3}{\lambda_1}$, implies:

$$\frac{w^P + t^F F_P - \frac{\lambda_2}{\lambda_1} M_F F_P}{\theta F_P} = \frac{w^E - s^E + t^F F_E - \frac{\lambda_2}{\lambda_1} M_F F_E}{\theta F_E - 1}. \tag{C.1.6}$$

Euler's Theorem and the degree one homogeneity of $F(\cdot)$ with respect to E and P, provides:

$$\begin{aligned} F &= F_E E + F_P P \Leftrightarrow \\ F_E &= \frac{1 - F_P \alpha_{PF}}{\theta}, \end{aligned} \tag{C.1.7}$$

where $\theta = \frac{E}{F}$ (when the mandate binds—the case we are interested in here) and $\alpha_{PF} \equiv$

$\alpha_{PF}\left(w^E - s^E, w^P, \theta\right) = \frac{P}{F}$. Which, after substituting (C.1.7) into (C.1.6), implies:

$$\frac{\lambda_2}{\lambda_1} M_F = \theta\left(w^E - s^E\right) + \alpha_{PF} w^P + t^F \equiv w^F, \tag{C.1.8}$$

where w^F is the retail price of blended fuel.

Euler's Theorem and the degree one homogeneity of $M(\cdot)$ with respect to F and L^H, provides:

$$\begin{aligned} M &= M_F F + M_H L^H \Leftrightarrow \\ M_F &= \frac{1 - M_H \alpha_{HM}}{\alpha_{FM}}, \end{aligned} \tag{C.1.9}$$

where $\alpha_{FM} = \frac{F}{M}$ and $\alpha_{HM} = \frac{H}{M}$. Which, after substituting into the first order condition for L^H, given (C.1.8) from above, yields:

$$\frac{\lambda_2}{\lambda_1} = \alpha_{FM} w^F + \alpha_{HM} \equiv w^M, \tag{C.1.10}$$

where w^M is the marginal cost of producing vehicle miles travelled. Defining $\hat{w}^M = w^M + \tau v$, where $v = 1 - t_L$ is the per mile price of travel time, which in this case is just equal to foregone net of tax wages. Note that $\hat{w}^M$ is the inclusive price of driving from the perspective of the consumer, which is inclusive of the value of travel time. Given these definitions, then the first-order conditions for the final consumer demands, N, X, and M, simplify down to:

$$\begin{aligned} C &: \frac{u_C}{\lambda_1} = 1, \\ X &: \frac{u_X}{\lambda_1} = w^X, \text{ and} \\ M &: \frac{u_M}{\lambda_1} = \hat{w}^M. \end{aligned} \tag{C.1.11}$$

Consequently, the unconditional consumer demand equations are given by:

$$\begin{aligned} C &= C\left(\theta, G\right), \\ X &= X\left(\theta, G\right), \\ M &= M\left(\theta, G\right), \\ E &= E\left(\theta, G\right), \\ P &= P\left(\theta, G\right), \text{ and} \\ L^H &= L^H\left(\theta, G\right). \end{aligned} \tag{C.1.12}$$

Plugging (C.1.12) into $u(\cdot)$ from (C.1.4), we obtain the indirect utility function:

$$V^D\left(\theta, G, K, T, D, J, Z\right) = v\left(\theta, G\right) + \xi(K) - \nu(T) - \psi(D) - \kappa(J) - \mu(Z). \tag{C.1.13}$$

Applying the Envelope Theorem to (C.1.4), we have:

$$\begin{aligned}
V_\theta^D \equiv \frac{\partial V}{\partial \theta} &= \frac{\lambda_3}{\lambda_1}F, \\
V_G^D \equiv \frac{\partial V}{\partial G} &= \lambda_1, \\
V_K^D \equiv \frac{\partial V}{\partial K} &= \xi'(\cdot), \\
V_T^D \equiv \frac{\partial V}{\partial T} &= -\nu'(\cdot), \\
V_D^D \equiv \frac{\partial V}{\partial D} &= -\psi'(\cdot), \\
V_J^D \equiv \frac{\partial V}{\partial J} &= -\kappa'(\cdot), \text{ and} \\
V_Z^D \equiv \frac{\partial V}{\partial Z} &= -\mu'(\cdot).
\end{aligned} \tag{C.1.14}$$

Now, given earlier first order conditions for E and P and (C.1.8), it is the case that:

$$\frac{\lambda_3}{\lambda_1} = \frac{F_E}{F_P} w^P - \left(w^E - s^E\right). \tag{C.1.15}$$

Recall, that the fuel blender's cost minimization problem is given by:

$$\begin{gathered}
\min_{E,P} \left(w^E - s^E\right) E + w^P P + t^F F \\
\text{subject to:} \\
F(E,P) \leq F \,(\lambda_4) \\
\theta F \leq E \,(\lambda_5)
\end{gathered} \tag{C.1.16}$$

Which, if the RFS is binding, then $\lambda_5 \geq 0$. Thus, given the first order conditions to (C.1.16), when this is the case we have:[1]

$$\frac{F_E}{F_P} w^P - \left(w^E - s^E\right) \leq 0. \tag{C.1.17}$$

Given (C.1.14) and (C.1.15), total differentiation of (C.1.13) with respect to θ, and a

[1] Note also that $\frac{F_E}{F_P} w^P - \left(w^E - s^E\right) \leq 0$ can be re-written as $\hat{\alpha}_{PF}\eta_{PF} - \hat{\alpha}_{EF}\eta_{EF} \leq 0$, where $\hat{\alpha}_{PF} = \frac{w^P P}{w^F F}$, $\hat{\alpha}_{EF} = \frac{\left(w^E - s^E\right)E}{w^F F}$, $\eta_{EF} = \frac{\partial E}{\partial F}\frac{F}{E}$, and $\eta_{PF} = \frac{\partial P}{\partial F}\frac{F}{P}$.

little re-arranging, we have:

$$\begin{aligned}
\frac{1}{\lambda_1}\frac{dV^D}{d\theta} &= \frac{V^D_\theta}{\lambda_1} + \frac{V^D_G}{\lambda_1}\frac{dG}{d\theta} \\
&\frac{V^D_K}{\lambda_1}\frac{dK}{d\theta} + \frac{V^D_T}{\lambda_1}\frac{dT}{d\theta} + \frac{V^D_D}{\lambda_1}\frac{dD}{d\theta} + \frac{V^D_J}{\lambda_1}\frac{dJ}{d\theta} + \frac{V^D_Z}{\lambda_1}\frac{dZ}{d\theta} \Leftrightarrow \\
\frac{1}{\lambda_1}\frac{dV^D}{d\theta} &= \left[F\left(\frac{F_E}{F_P}w^P - \left(w^E - s^E\right)\right)\right] + \frac{dG}{d\theta} + \mathbf{A},
\end{aligned} \tag{C.1.18}$$

where:

$$\begin{aligned}
\mathbf{A} &= \frac{\xi'}{\lambda_1}\frac{dK}{d\theta} - \frac{\nu'}{\lambda_1}\frac{dT}{d\theta} - \frac{\psi'}{\lambda_1}\frac{dD}{d\theta} - \frac{\kappa'}{\lambda_1}\frac{dJ}{d\theta} - \frac{\mu'}{\lambda_1}\frac{dZ}{d\theta} \Leftrightarrow \\
\mathbf{A} &= \frac{\xi' K'}{\lambda_1}\frac{dA_N}{d\theta} - \left[\frac{\nu'\tau'}{\lambda_1} + \frac{\psi' D'_M}{\lambda_1} + \frac{\mu' Z'}{\lambda_1}\right]\left(\frac{dM}{d\theta}\right) - \frac{\psi' D'_{GHG}}{\lambda_1}\left[\left(\frac{d\frac{E}{F}}{d\theta}\right) + \left(\frac{dF}{d\theta}\right)\right] \\
&- \frac{\kappa' J'}{\lambda_1}\left(\frac{dP}{d\theta}\right) \Leftrightarrow \\
\mathbf{A} &= MEB^N\frac{dA_N}{d\theta} \\
&- \left[\frac{\nu'\tau'}{\lambda_1} + MD^M_{LP} + MD^M_A\right]\left(\frac{dM}{d\theta}\right) - MD^{GHG}\left[\left(\frac{d\frac{E}{F}}{d\theta}\right) + \left(\frac{dF}{d\theta}\right)\right] \\
&- MEC^P\left(\frac{dP}{d\theta}\right).
\end{aligned} \tag{C.1.19}$$

Total differentiation of the government's budget constraint provides:

$$\frac{dG}{d\theta} = -t^L\frac{d\tau M}{d\theta} + t^F\frac{dF}{d\theta} - s^E\frac{dE}{d\theta} - s^N\frac{dA_N}{d\theta}. \tag{C.1.20}$$

Continuing from (C.1.18) after multiplying through by -1 and substituting in (C.1.20), we have:

$$\begin{aligned}
-\frac{1}{\lambda_1}\frac{dV^D}{d\theta} &= \left[F\left(\left(w^E - s^E\right) - \frac{F_E}{F_P}w^P\right)\right] + s^E\left(\frac{dE}{d\theta}\right) \\
&\left[\left\{MD^{GHG}\left(\left(\frac{d\theta}{dF}\right) + 1\right) + \left[MD^M_C + MD^M_{LP} + MD^M_A\right]\left(\frac{dM}{dF}\right)\right\}\right. \\
&\left. - t^F\right]\left(\frac{dF}{d\theta}\right) \\
&+ MEC^P\left(\frac{dP}{d\theta}\right) + \left(MEB^N - s^N\right)\left(-\frac{dA_N}{d\theta}\right).
\end{aligned} \tag{C.1.21}$$

Now define:

$$MPC = \left(w^F + F \left(\frac{dw^F}{dF} \right) \right), \tag{C.1.22}$$

$$MEC_F = \left(MEC^{GHG} \left(\left(\frac{d\theta}{dF} \right) + 1 \right) + MEC^M \left(\frac{dM}{dF} \right) \right), \tag{C.1.23}$$

$$MEC^{GHG} = \left(\frac{\psi' D'_{GHG}}{\lambda} \right), \tag{C.1.24}$$

$$MEC^P = \frac{\kappa' J'}{\lambda}, \tag{C.1.25}$$

$$MEB^N = \frac{\xi' K'}{\lambda}, \tag{C.1.26}$$

$$MEC^M = \left(MEC_A^M + MEC_C^M + MEC_{LP}^M \right), \tag{C.1.27}$$

$$MEC_A^M = \frac{\mu' Z'}{\lambda},\ MEC_C^M = \tau' \left(t^L + \frac{\nu'}{\lambda} \right),\ MEC_{LP}^M = \frac{\psi' D'_M}{\lambda}. \tag{C.1.28}$$

Then (C.1.21), given (C.1.22) provides the remaining terms in (3.3.24).

C.2 Other Biofuel Support Programs

C.2.1 RFS for Advanced Biofuels

The RFS for advanced biofuels expands from 0.6 billion gallons in 2009 to 5.5 billion gallons in 2015, and reaches a maximum of 21.0 billion gallons by 2022. The RFS for advanced biofuels applies to any biofuel that achieves 50% lifecycle emissions savings or greater. Advanced biofuels span three dominant technologies: cellulosic ethanol, biomass based diesel, and sugarcane ethanol as imported from Brazil and Caribbean Basin Initiative (CBI) countries. In the short-run, up to 2015, which is the focus of our analysis, each technology faces challenges for expansion. We discuss these challenges in greater detail in Bento et al. (2013b), but suffice to say there are legitimate reasons to be skeptical as to whether the volumes for advanced biofuels specified under EISA 2007 will actually be achieved in the short run and at volumes large enough to be of major economic consequence.[2] Given this, as as well as the lack of credible data on feedstock production and technological conversion efficiency for advanced biofuels, we do not consider the RFS for advanced biofuels in our analysis.

[2]Of these three, the RFS for cellulosic ethanol comprises the largest share of the RFS for Advanced biofuels, with EISA 2007 establishing a cellulosic ethanol mandate of 3.0 billion gallons ny 2015, and 16.0 billion gallons by 2022. This is the weakest mandate in the RFS as policymakers included a "cellulosic loophole" in EISA 2007 (specifically, CAA section 211(o)(7)(D)(i)) which effectively allows the EPA to scale down the RFS for cellulosic biofuels if production is not there. In the final rules for 2010, 2011, and 2012, the EPA has in fact exercised this legal authority, lowering the effective RFS for cellulosic biofuels *to* 7%, 3%, and 2%, respectively, of the statutory level stated in EISA 2007. For example, the 2012 RFS for Cellulosic ethanol requires 0.5 billion gallons be blended into the nation's fuel supply, but this was revised to 0.01 billion gallons, which is the amount of cellulosic ethanol currently being produced in the US. Since policymakers included this loophole in EISA 2007, it should not affect our calculation of the implicit value that policymakers place on oil dependency.

C.2.2 Other Policies that Impact Ethanol

While the RFS and VEETC influence the total amount of ethanol used in the US, several states encourage biofuel adoption through state-level biofuel mandates. Likewise, in California biofuels can be used to comply with the Low Carbon Fuel Standard. An assortment of ethanol production subsidies, loan guarantees, and tax credits are also prevalent at the state level.[3] These state policies are generally of significantly smaller scope and impact than the two federal programs that are the focus of this paper.[4]

C.3 Functional Forms

We use a numerical model with the same general structure as our analytical model to quantify each the welfare impacts of the RFS for the years 2009-2015. Here we lay out the key functional form assumptions used in the numerical model.

Consumer

The representative agent is assumed to have preferences given by the following nested constant elasticity of substitution (CES) utility function:

$$\begin{aligned} U(F, L^H, X, C) &= \left[\alpha_U M(F, L^H)^{\frac{\sigma_U - 1}{\sigma_U}} + (1-\alpha_U)\, W(C, X)^{\frac{\sigma_U - 1}{\sigma_U}}\right]^{\frac{\sigma_U}{\sigma_U - 1}} \\ W(C, X) &= \gamma_W \left[\alpha_W C^{\frac{\sigma_W - 1}{\sigma_W}} + (1-\alpha_W)\, X^{\frac{\sigma_W - 1}{\sigma_W}}\right]^{\frac{\sigma_W}{\sigma_W - 1}} \\ M(F, L^H) &= \gamma_M \left[\alpha_M F^{\frac{\sigma_M - 1}{\sigma_M}} + (1-\alpha_M)\, {L^H}^{\frac{\sigma_M - 1}{\sigma_M}}\right]^{\frac{\sigma_M}{\sigma_M - 1}} \end{aligned} \tag{C.3.1}$$

where W is a composite of food and other consumption, M denotes vehicle miles travelled (VMT)[5] and L^H denotes fixed costs of driving. σ_U, σ_W, and σ_M are elasticities of substitution, $\alpha_U, \alpha_W, \alpha_M$ are share parameters, and γ_W and γ_M are scale parameters. Nesting utility in this way implies weak-separability between VMT and other consumption. In embedding the VMT decision we permit substitutability between fixed costs of driving and blended fuel allowing fuel economy to be endogenously determined.

Land Use Allocation

The land owner's decision closely follows equation (3.3.13), except that we consider five crops, corn soybeans, wheat, hay and cotton, as well as land allocated to the CRP.[6] We assume that the yield (payment) functions in (3.3.13) is linear in the quantity of land allocated to

[3] For a complete list of state level biofuel policies see the US Department of Energy's Alternative Fuels & Advanced Vehicles Data Center (http://www.afdc.energy.gov/afdc/laws/state).

[4] The combination of state-wide MTBE bans and non-compliance with the National Ambient Air Quality Standards of the 1990 Clean Air Act Amendments also generated implicit ethanol mandates in some metropolitan areas. However, in the time frame of our analysis, crude oil prices high enough that these implicit mandates will not bind.

[5] We use "miles" and "VMT" in the description here because it follows the literature. We report values in kilometers to maintain consistency in metric units throughout the paper.

[6] The subscript i in equation (3.3.13) now indexes six land uses.

each land use (A_i):

$$y_i(A_i) = \beta_i - \delta_i A_i \tag{C.3.2}$$

where β_i and δ_i are the intercept and exogenous slope coefficients of crop i's linear yield function.

Only corn is used to produce ethanol, while corn, soybeans, hay and wheat are all used in food production. Corn, soybeans, wheat and cotton are exported to the rest of the world.

Fuel Markets

Fuel blenders, equation (3.3.6) in the analytical model, are constrained by a linear production function:

$$F = \Gamma_F E + P \tag{C.3.3}$$

where Γ_F is set so that ethanol and gasoline are energy equivalent perfect substitutes. Our treatment of blended fuel production as energy equivalent perfect substitutes is similar to the approach taken by de Gorter and Just (2009) but contrasts with Khanna et al. (2008), who use a constant elasticity of substitution (CES) functional form for this sector. We believe such a functional form is overly restrictive given that the share parameters entering that function are not endogenous and instead fixed to calibration year data. Unlike de Gorter and Just (2009), however, we solve for the share of ethanol in the absence of the RFS, using the first-order conditions of the profit maximization problem when the RFS constraint is not present.

When the RFS is not binding or not present, the fuel blender's profit maximization problem implies:

$$\Gamma_F = \frac{w^E - s^E}{w^P}. \tag{C.3.4}$$

We can identify the share of ethanol in blended fuel, $\Theta = \frac{E}{F}$, such that the above condition holds. In this case the price of blended fuel in the baseline is given by: $w^F = \left(w^E - s^E\right)\Theta + w^P\left(1 - \Gamma^F\Theta\right) + t^F$. In contrast, the price of blended fuel when the RFS is binding is given by: $w^F = \left(w^E - s^E\right)\theta + w^P\left(1 - \Gamma^F\theta\right) + t^F$, when the VEETC is renewed, and $w^F = w^E\theta + w^P\left(1 - \Gamma^F\theta\right) + t^F$, when the VEETC is allowed to expire.

When the VEETC is renewed, the change in the price of blended fuel due to the RFS is given by: $w_1^F - w_0^F = \theta w_1^E - \Theta w_0^E - s^E\left(\theta - \Theta\right) + \left(1 - \Gamma^F\theta\right)w_1^P - \left(1 - \Gamma^F\Theta\right)w_0^P$, where superscripts denote post-policy (1) and baseline (0). However, when the VEETC is allowed to expire, the change in the price of blended fuel due to the RFS is given by: $w_1^F - w_0^F = \theta w_1^E - \Theta w_0^E + s^E\Theta + \left(1 - \Gamma^F\theta\right)w_1^G - \left(1 - \Gamma^F\Theta\right)w_0^P$. Note that while, $s^E\left(\theta - \Theta\right)$ is very close to zero (the change in the share of ethanol in blended fuel, $\theta - \Theta$ is very small), $s^E\Theta$ is not, reflecting the fact that when the RFS is imposed the full change in the price of ethanol is now passed along to the consumer through the change in the price of blended fuel.

Ethanol is produced according to a Leontief production function:

$$E\left(Y^E, L^E\right) = \min\left\{\frac{Y^E}{\lambda_{E,Y}}, \frac{L^E}{\lambda_{E,L}}\right\} \tag{C.3.5}$$

where Y^E is corn used for ethanol production and L^E is expenditures on labor, and $\lambda_{E,Y}$

and $\lambda_{E,L}$ are exogenous parameters that determine much corn and labor are required to produce a unit of ethanol. Ethanol is actually a joint production process which produces, in addition to ethanol, 'co-products' which can be used in place of grains in livestock feeds. We consider four co-products, dried distillers grains, corn gluten meal, corn gluten feed, and corn oil which are used in food production.[7]

Gasoline production is modeled with a nested constant returns to scale CES technology:

$$P\left(R^P, L^P\right) = \gamma_P \left[\alpha_P {R^P}^{\frac{\sigma_P - 1}{\sigma_P}} + \left(1 - \alpha_P\right) {L^P}^{\frac{\sigma_P - 1}{\sigma_P}}\right]^{\frac{\sigma_P}{\sigma_P - 1}} \tag{C.3.6}$$

where α_P is a share parameter, γ_P, is a scale parameter, and σ_P is the elasticity of substitution.

World Crop Demand

The rest-of-world consumption of US agricultural products is specified according to inverse excess (or import) demand functions:

$$p^i = \gamma_i \left({i^{X,W}}^{\frac{1}{\eta_i}}\right) \tag{C.3.7}$$

where $i^{X,W}$ is the amount of crop i demanded (net of supply) by the rest of the world, γ_i is a scale parameter for the crop i demand function, and η_i is the rest-of-world excess demand elasticity for crop i. Here i corresponds to trade in agricultural products with respect to the rest of the world, that is i spans corn, soybeans, wheat, and cotton. We note that equation (C.3.7) for corn, soybeans, and wheat reflects total rest-of-world export demand for these agricultural products. Food and ethanol production account for total US demand for these crops in the model. Since cotton is not an input in food production, we treat (C.3.7) as total demand for cotton in order to close the model; in this case, (C.3.7) reflects rest-of-world demand for cotton exports as well as total US demand for cotton.[8] Finally, given changes in crop exports, we impute how cropland expands at the expense of non-agricultural land uses, A_N^W, in the rest-of-world economy, which is used to assess the impact of international land-use adjustments on GHG emissions (see Section C.6, below).

Net Crude Oil Supply

We consider a simple model of crude oil supply that abstracts from market power considerations with respect to the production and refinement of crude oil. We specify the inverse net excess supply of crude oil as:

$$p^R = \gamma_R \left({R^W}^{\frac{1}{\eta_R}}\right) \tag{C.3.8}$$

[7] We assume that these four co-products are produced in fixed proportion to the amount of ethanol produced and are combined, in terms of corn and soybean equivalents, with the corn and soybeans used in food production. The value of co-products, which is endogenous, is taken as a rebate to the ethanol producer, and therefore subtracted from the marginal cost of producing ethanol.

[8] This assumption means that to calculate the change in the trade balance due to cotton exports by the US to the ROW, we need to net out the component of demand that is due to US consumption of cotton. This is discussed in greater detail below.

where R^W is the net amount of crude oil supplied to the US (net of US demand for crude oil for non-gasoline uses and US supply of crude oil, see below), γ_R is a scale parameter, and η_R is the supply elasticity for crude oil.[9]

Food Production

Food production is modeled as a set of nested constant returns to scale CES functions:

$$
\begin{aligned}
X(Y^i, L^X) &= \gamma_X \left[\alpha_X {L^X}^{\frac{\sigma_X - 1}{\sigma_X}} + (1 - \alpha_X)\, Q(Y^i)^{\frac{\sigma_X - 1}{\sigma_X}} \right]^{\frac{\sigma_X}{\sigma_X - 1}} \\
Q(Y^i) &= \gamma_Q \\
&\quad \left[\alpha_{Y^3} {Y^3}^{\frac{\sigma_Q - 1}{\sigma_Q}} + \alpha_{Y^4} {Y^4}^{\frac{\sigma_Q - 1}{\sigma_Q}} + (1 - \alpha_{Y^3} - \alpha_{Y^4})\, V(Y^1, Y^2)^{\frac{\sigma_Q - 1}{\sigma_Q}} \right]^{\frac{\sigma_Q}{\sigma_Q - 1}} \\
V(Y^1, Y^2) &= \gamma_V \left[\alpha_V {Y^1}^{\frac{\sigma_V - 1}{\sigma_V}} + (1 - \alpha_V)\, {Y^2}^{\frac{\sigma_V - 1}{\sigma_V}} \right]^{\frac{\sigma_V}{\sigma_V - 1}}
\end{aligned}
\tag{C.3.9}
$$

where L^X is the amount of labor used in food production, Q is a composite feedstuffs index including the four food crops and co-products, V is a composite index including corn, soybeans and co-products, Y^i is the amount of crop i needed to produce food.[10] σ_X, σ_Q, and σ_V are elasticities of substitution, α_X, α_{Y^3}, α_{Y^4} and α_V are share parameters, and γ_X, γ_Q and γ_V are scale parameters. Here, Y^1 and Y^2 are corn and soybeans used by the food sector net of ethanol co-products.

C.4 Data and Calibration

Benchmark Economy

Table C.3 presents the characteristics of the US economy for the calibration year, 2003. We chose to calibrate using 2003 data because it precedes several anomalous years prior to our period of analysis, where crop and crude oil prices were well above historic levels. Also, our primary data source for agricultural input data, the USDA's Economic Research Service (ERS) *Agricultural Resource Management Survey* (ARMS), is conducted for each major crop on a rotating quadrennial basis and 2003 is the central year of a recent four year cycle. In 2003, US GDP was roughly \$7.7 trillion. This includes net government transfers to households of \$2.9 trillion, which we assume here is financed from revenue raised from a uniform tax of 36.6% on the representative agent's labor endowment. This implies an after-tax value of the labor endowment of \$4.8 trillion.[11] The net returns from land holdings comprise the remainder of GDP, \$27.6 billion, which is small in comparison to total GDP.

In 2003, 112.68 million hectares of cropland were allocated to the five crops considered. These crops represent more than 90% of principle cropland harvested and more than 80% of the value of field crop production in 2003 according to USDA National Agricultural Statistics

[9] This assumption means that to calculate the change in the trade balance due to crude oil import to the US from the ROW, we need to net out these other components. This is discussed in greater detail below.

[10] The crops are indexed as follows, corn ($i = 1$), soybeans ($i = 2$), hay ($i = 3$), and wheat ($i = 4$).

[11] These figures were taken from the US Bureau of Economic Analysis *National Income and Product Accounts* (NIPA) dataset.

Service (NASS) data. Corn was the dominant crop in terms of land area, at 31.37 million hectares, followed by soybeans, hay, wheat and cotton. In addition to cropland, 13.57 million hectares were held as CRP. This is the sum of land held in the general sign-up and continuous non-CREP CRP programs and accounts for close to 95% of total land held as CRP, according to the USDA's Farm Service Agency *Conservation Reserve Program Statistics* (CRPS). We intentionally exclude those categories of CRP land which are not likely to be converted back into crop production, given the higher rental payments that are received or the services they provide, such as rare habitat conservation, riparian buffers, etc. The average CRP rental rate was $114.48 per hectare.[12] Crop prices represent national average prices (paid to the farmer) reported to the USDA's National Agricultural Statistics Service (NASS). Average yields in the US for corn, soybeans, hay, wheat and cotton are also from NASS.

Blended fuel consumption in 2003 was 497.21 billion liters, of this regular gasoline made up 490.28 billion liters. This implies that 3.12 billion barrels of crude oil was used for gasoline in 2003, which is consistent with the US Energy Information Administration's (EIA) *US Crude Oil Supply & Disposition* (CSD) dataset. Total ethanol consumption was 10.39 billion liters according to the US Federal Highway Administration's *Highway Statistics 2003* (FHWA). The price of regular gasoline, $0.23 per liter, is the consumption weighted US average spot price for all grades of conventional gasoline from the EIA's *Annual Energy Review 2008*. We compute a spot price for ethanol in 2003 of $0.35 per liter, which is the marginal cost of ethanol production less the value of co-products sold to food producers. This is very close to the average 2003 spot price for deliveries to Omaha, Nebraska of $0.36 per liter according to Nebraska's *Unleaded Gasoline and Ethanol Average Rack Prices* data.[13] Given benchmark quantities and prices of gasoline and ethanol, the 2003 price of blended fuel is $0.41 per liter, inclusive of the VEETC.

Consumer

We specify elasticities of substitution between miles and non-mile expenditures, σ_U in (C.3.1), of 0.50, between food and the composite good, σ_W in (C.3.1), of 0.09, and between fuel and non-fuel expenditures on driving, σ_M in (C.3.1), of 0.21. We selected these in order to imply a calibrated own-price elasticity of demand for food of -0.12, an own-price elasticity of demand for blended fuel of -0.34, and a cross-price elasticity of demand for VMT with respect to the price fuel of -0.22.

Estimates of the own-price elasticity of food demand are sparse. Our estimate is roughly consistent with the estimates of Seale et al. (2003), who report own-price elasticity for a broad consumption group of "food, beverages and tobacco" in the range of -0.075 to -0.098. We adopt a slightly more elastic value then the upper bound from that study, given that the own-price demand elasticity for tobacco is likely very small and is not represented in our treatment of the food sector here.

Our calibrated own price elasticity of demand for blended fuel is consistent with empirical

[12]This value was computed from the CRPS and represents the weighted average annual rental payment to land in the general sign-up and non-CREP continuous sign-up programs.

[13]Historic ethanol price data is limited. Most spot prices for ethanol are reported as the price of free-on-board deliveries to various rural locations in the Midwest, where ethanol has historically been produced. Spot prices to locations outside of the Midwest exist only for the last few years. Since our spot price for regular gasoline reflects the national average, it is necessary to adjust the non-corn input expenditures accordingly.

estimates. In particular, our estimate is slightly lower than the best estimate proposed by the US Department of Energy of 0.38 (DOE, 1996), and considerably smaller than the central value of 0.55 assumed by (Parry and Small, 2005). We choose a smaller value in order to be consistent with more recent estimates which report a smaller value (Small and Dender, 2007).

Our calibrated own-price elasticity of demand for miles with respect to the price of blended fuel is well within the central estimates provided by the literature and is consistent with the value implied by Parry and Small (2005). Summaries of this literature (see De Jong and Gunn (2001); Graham and Glaister (2002); Goodwin et al. (2004)) report means for short-run estimates between -0.10 and -0.26 and long-run estimates of -0.26 and -0.34.

Given calibration year crop production and export shares, and the total value of food, this implies the representative agent spends 0.035 of their income on food. Given calibration year data on fuel prices, fuel quantities, and miles-traveled, and assuming that the share of fixed costs of driving to total costs of driving was 0.60, this implies that the share of income spent on VMT was 0.065. We note that these expenditure shares are lower than those computed from the US Bureau of Economic Analysis' (BEA) for 2003 of 0.091 and 0.082 respectively.[14] However, we believe that precisely calibrating the relationship of fuel prices to the price of miles-traveled and the relationship of crop prices to the price of food is of greater importance for determining the equilibrium price effects of RFS. [15]

Fuel Production

The ratio of the energy content of ethanol to gasoline, $\Gamma^F = 0.67$, is based on the low heating values of each fuel. Our linear specification for the production of blended fuel is not calibrated to an estimate of the elasticity of blended fuel. Rather, the elasticity of blended fuel will be determined only by the underlying elasticities of gasoline and ethanol.

Gasoline Production

We assume an elasticity of substitution between crude oil and labor in the production of gasoline, σ_P, of 0.06. This was selected to approximate a perfectly complementary relationship between crude oil and labor in the production of gasoline.

The price of gasoline faced by the fuel blender is calibrated to the average spot price for conventional, regular grade gasoline in 2003.[16]

Ethanol Production

The per unit ethanol input requirements in equation (C.3.5), are calibrated to reflect an average ethanol production facility in the US. In 2003, we assume that the corn to ethanol

[14] These small differences in expenditure shares are likely due to definitional differences between the national accounts data and those implied by our model. The food share from the BEA is total expenditures in the 'Food' sub-heading divided by total GDP, less net exports. The VMT share is the sum of 'Motor vehicle and parts', 'Gasoline, fuel oil, and other energy goods', and 'Transportation' sub-headings divided by total GDP, less net exports.

[15] Another source, which although more dated provides a finer definitional resolution for making comparisons, is the BEA's *Benchmark Input and Output Tables for 1992*. This dataset provides expenditure shares of 0.041 and 0.055, respectively, which are markedly closer to our estimates.

[16] Average here means population weighted average price of PADDs 1, 3, and 5. PADDs 1, 3, and 5, are considered as these are the PADDs for which spot price data is readily available. Combined these three PADDs account for 69% of the total US population.

conversion ratio is 2.56 kg per liter (GREET 1.8c Wang (2009)). We also assume that with each liter of ethanol co-products equivalent to 0.7 kg corn and 0.03 kg soybeans are produced (GREET 1.8c Wang (2009)).

To construct parameters for a national average ethanol producer, we consider four ethanol production technologies, which are combinations of conversion technology (wet or dry milling) and fuel source (natural gas or coal). These categories are used because wet milling and dry milling are inherently different technologies, produce different co-products and have different corn and energy requirements. In 2003, dry mills fired by natural gas and coal account for 39.4% and 12.9% of total ethanol production respectively. Wet mills fired by natural gas account for 5.4% of total production and wet mills fired by coal make up the remaining 42.3%. These shares are derived from ethanol plant start up dates reported by the EPA (2010).

Labor inputs to ethanol production are calculated as total expenditures on energy, transportation costs, labor and capital for ethanol production. Following Farrell et al. (2006), we assume that the energy requirements of ethanol production are 13.2 MJ/liter, which represents a combination of natural gas, coal and electricity. Average expenditures on labor and capital for ethanol production are assumed to be 0.0053 $/liter and 0.063 $/liter. These values are consistent with values reported by an industry survey (Shapouri and Gallagher, 2005).

We estimate the quantity of co-products produced per unit ethanol using equations from GREET 1.8c Wang (2009). In the benchmark 0.52 kg of distillers' grains, 0.03 kg of corn gluten meal, 0.13 kg of corn gluten feed and 0.02 kg of corn oil are jointly produced with each unit of ethanol. Consistent with the EPA (2010), we assume a kilogram of distiller's dried grains displaces 0.95 kilograms of corn and 0.05 kilograms of soybeans. A kilogram of corn gluten feed displaces 1.53 kilograms of corn and a kilogram of corn gluten meal displaces 1.0 kilograms of corn. We allow corn oil to displace corn based on its economic value in 2003, such that $1 of corn oil displaces $1 of corn.[17]

Transportation costs incurred by the ethanol producer are also accounted for. First, we assume that the cost of shipping ethanol to its final destination is incurred by the ethanol producer. The cost of shipping ethanol is $0.032 per liter, which is the PADD average tariff plus rate plus fuel surcharge per liter ethanol weighted by PADD level ethanol consumption. We also assume that the cost of shipping co-products to their final destination is subtracted out from the revenue the ethanol producer receives from selling co-products. The average cost of shipping co-products is 0.029 $/kg, in constant 2003 dollars. This value is calculated using data on rail costs for transporting DDGs from data compiled by the USDA.

We estimate transportation costs based on USDA data for the average tariff rate plus fuel surcharge per liter ethanol delivered to each PADD, and the rail costs for transporting co-products. Both data series are compiled by the USDA from freight companies (BNSF, UP, CSX, and NS) websites for May 2010. To calculate the average ethanol transportation costs from the USDA data, we approximate the percent of the national total refinery and blender net inputs of fuel ethanol by PADD using data from the EIA on Refinery and Blender Net

[17] We use this method because corn oil is utilized for much more than just an animal feed, and therefore the typical displacement ratio methods used are not reflected in the historic prices of the two products (Shapouri and Gallagher, 2005).

Inputs of Fuel Ethanol by PADD for the years 2000-2009. To calculate the average costs of shipping co-products from the USDA data, we take an average across all data points and assume that 30% of co-products are transported locally at zero cost to the ethanol plant.[18]

RFS Share Mandate

The RFS share mandate, θ, is computed by partially solving the model while treating several of the model outputs from the estimated baseline as fixed. First, we predict the amount of corn required to meet the additional production of ethanol given the quantity of ethanol mandated by the RFS. From this estimated change in corn production, we estimate the resulting change in crop prices, as well as the change in the net returns to the land endowment. From the change in the price of corn, impute the resulting change in the price of ethanol, regular gasoline and crude oil, and thus also the change in the price of blended fuel and VMT. Using these projections, we are able to generate an estimate of final total blended fuel demand, conditional on the RFS. Dividing the published RFS volumes by estimated total blended fuel demand identifies an estimate of θ.

Land Use Allocation

To construct the per-unit land labor expenditures for agricultural production (l_i in equation (3.3.13)), we sum expenditures over four broad input categories: labor, capital, energy and fertilizer (Table C.6). Expenditures on labor and capital are from the USDA's ERS *Commodity, Costs and Returns* (CCR) dataset. Capital expenditures include interest on operating capital and the capital recovery of machinery and equipment. Labor expenditures include the wages and the opportunity costs of unpaid workers.

We construct energy and fertilizer expenditures from detailed input use data and subsequently use this data to calculate crop specific emissions factors (discussed below). Our estimates for energy expenditures are aggregate expenditures on diesel, gasoline, natural gas, electricity and liquefied petroleum gas. Diesel use for each crop was derived from West and Marland (West and Marland, 2002) and (Nelson et al., 2009). Crop specific use of the other energy sources were derived from the lifecycle analysis literature (Farrell et al., 2006; Hill et al., 2006; Piringer and Steinberg, 2006). Fertilizer expenditures represent expenditures on all variable inputs that are not categorized as energy, capital or labor and are constructed from two main sources. First, expenditures on nitrogen, phosphorus, and potassium fertilizer, pesticide and seed are calculated using crop level input use data from ARMS and national prices from the USDA's ERS *Fertilizer Use and Price*.[19] Second, expenditures on other variable inputs are from the CCR.[20] Fertilizer expenditures are disaggregated in the lower panel of Table C.6.

[18]The USDA data reports the tariff rate plus fuel surcharge per unit of co-products between various origin and destination cities.

[19]Input data for hay is not available in the ARMS, so fertilization rates were collected from extension reports from institutions in major hay producing regions. Application levels were based on recommendations given a medium or optimal soil test.

[20]This includes expenditures on soil conditioners, manure, custom operations, repairs, purchased irrigation water, taxes and insurance, and general farm overhead.

Land Supply Elasticities

The six δ_i in (C.3.2) are selected in order to match the supply response of the US land market to the elasticities taken from the literature and reported in Table C.5. Given the six δ_i, we select the six β_i in (C.3.2) in order to match the yields reported in Table C.3 in 2003, and adjusted each year afterwards to reflect exogenous growth in crop yields over time (see Section C.4.1 below). Given the structure of the model, these β_i can be solved for as a function of δ_i such that the implied yields are almost identical to the targeted yields. To improve precision in matching estimated supply response to literature estimates, we re-calibrate the δ_i parameters each year to construct our baseline, and then again for each counterfactual run.

To select each δ_i vector, we perform an exhaustive search that seeks to minimize the error between the supply response implied between two model runs (taking the equilibrium resulting from the previous run as exogenous data) and the supply response implied by Table C.5 given the percent change in crop prices between the two model runs. Each search is highly non-linear and takes several days to complete. To improve computational time and precision, we exploit several optimization algorithms, including modern heuristic algorithms such as the Local Multistart Radial Basis Function (LMSRBF) algorithm developed by Regis and Shoemaker (2007). We repeat this using multiple random re-starts and choose the vector that achieves the best supply response from the resulting candidates. The initial 2003 δ_i vector was selected to match supply response resulting from a 1% exogenous increase in ethanol. All baseline δ_i vectors are selected recursively using the preceding year's baseline equilibrium as exogenous data, starting from the 2003 baseline equilibrium. Each counterfactual δ_i vector for a given year is selected using the baseline equilibrium for that year as exogenous data. We isolate the δ_i vector for each baseline run using a baseline in which the VEETC is in place. We isolate the δ_i vector for each counterfactual run for our first regime which compares the RFS with the VEETC to the baseline in which the VEETC is in place. In total, these searches took about six months to complete.

To demonstrate the success of this approach, we point to the exhaustive validation exercise we perform in Section C.5 that attempts to demonstrate that the predicted land response of our model is in line with observed outcomes. We match observed land patterns well and our predictions for later years are in line with USDA Long-Term projections that pre-date the RFS.

Rest-of-world Crop Demand

Corn, Soybean, and Wheat Exports

The crop export demand elasticities, η_i in equations (C.3.7), are set to -0.65, -0.60, and -0.55 for corn, soybeans, wheat and cotton respectively, which represent the central values reported in Gardiner and Dixit (1987).

Cotton Exports

Total demand for cotton is given by:

$$Q_{i=5} = D_{i=5}^{US+ROW} = NX_{i=5}^{ROW} + D_{i=5}^{US}, \tag{C.4.1}$$

where, $NX_{i=5}^{ROW} = D_{i=5}^{ROW} - S_{i=5}^{ROW}$ is the net demand for cotton imports from the US from the ROW.

Differentiating (C.4.1) with respect to the price of cotton and solving for the elasticity of total demand, $\eta_{i=5}$, we have:

$$\eta_{i=5} = \eta_{D,i=5}^{US+ROW} = \eta_{NX,i=5}^{ROW}\left(\frac{NX_{i=5}^{ROW}}{D_{i=5}^{US+ROW}}\right) + \eta_{D,i=5}^{US}\left(\frac{D_{i=5}^{US}}{D_{i=5}^{US+ROW}}\right). \tag{C.4.2}$$

To calibrate $\eta_{i=5}$ using (C.4.2) we use data for 2003 quantities from the USDA's Foreign Agricultural Service (FSA) *Production, Supply and Distribution Online* (PSD) dataset. According to this dataset, net cotton exports from the US to the ROW were 6.6 billion pounds in 2003. Total US demand in 2003 is 3.1 billion pounds. This implies a total quantity of cotton supplied by the US in 2003 of 9.7 billion pounds. Consequently, $\left(\frac{NX_{i=5}^{ROW}}{D_{i=5}^{US+ROW}}\right) = 0.68$ and $\left(\frac{D_{i=5}^{US}}{D_{i=5}^{US+ROW}}\right) = 0.32$. We assume a value of $\eta_{NX,i=5}^{ROW}$ of -0.75, which is the central value reported in Gardiner and Dixit (1987). We assume a value of $\eta_{D,i=5}^{US}$ of -0.75, which implies that $\eta_{i=5}$ is also -0.75.

Rest-of-world Land Use

In absence of a fully specified world land use model, we linearly relate reductions in US crop exports to reductions in world agricultural land. Specifically, we assume that 44%, 50%, 47% and 50% of reduced US corn, soybean, wheat and cotton exports are replaced by expanded agricultural production in the rest of the world at non-US average yields. These shares are given by:

$$\gamma_{ROW,i} = \frac{-\eta_{S,i}^{ROW} S_i}{\eta_{D,i}^{ROW} D_i - \eta_{S,i}^{ROW} S_i} \tag{C.4.3}$$

where $\eta_{S,i}^{ROW}$ and $\eta_{D,i}^{ROW}$ are the rest-of-world elasticities of supply and demand for crop i, and D_i and S_i are the rest-of-world demand and supply for crop i. The elasticity values are taken from the FAPRI *Searchable Elasticity Database* and the supply and demand quantities are 2003 values reported by the USDA's Foreign Agricultural Service (FSA) *Production, Supply and Distribution Online* (PSD) dataset.

In our central case, the percentages of reduced US crop exports replaced by expanded agricultural production are broadly consistent with range of values implied by earlier studies by Searchinger et al. (2008) and the US EPA (2010).[21] More recent studies, such as Hertel et al. (2010), argue that the earlier analyses overestimate world land use change because they fail to account for factors that may mitigate a portion of the expansion in world agricultural production such as price induced yield improvements and crop demand adjustments. To address the uncertainty in the literature, as sensitivity analysis we consider high and low cases

[21] The results of Searchinger et al. (2008) imply that 50%, 82% and 52% of reduced US corn, soybeans and wheat exports are replaced by expanded production worldwide. Similar percentages are implied in the US EPA (2010) study for corn and soybeans in 2015, 65% and 67% respectively. However, world land allocated to wheat declines in this year, despite reduced US wheat exports.

where the percentage of US crop exports replaced by expanded world production for each crop are increased and decreased by 20% from the central value. The high case represents a world with a more inelastic world demand for agricultural products and where yields respond inelastically to price increases. The low case represents the case where reductions in crop demand and price induced yield improvements soften the link between reduced US exports and rest-of-world land use change.

Rest-of-world Crude Market

The model framework presented above considers the excess supply of crude oil going to the US for gasoline consumption, R. To calibrate the elasticity of excess supply facing US gasoline producers and to calculate the impact of the RFS on rest of world crude oil consumption we rely on a simple model of the international crude oil market. An important feature of our framework is that we incorporate all US crude oil demand for purposes other than gasoline production, as well as all US supply of crude oil, in our specification of the international crude oil market.[22]

Imposing market clearing in the international market for crude oil implies:

$$R = D^{US}_{Gas} = S^{ROW}_{Crude} + S^{US}_{Crude} - D^{ROW}_{Crude} - D^{US}_{Dist} - D^{US}_{Other} \tag{C.4.4}$$

where, D^{US}_{Gas} is the amount of crude oil demanded for gasoline in the US market, D^{US}_{Dist} is the amount of crude oil demanded for distillate fuels in the US market, D^{US}_{Other} is the amount of crude oil demanded for all other crude products (which includes residual fuels, jet fuel, kerosene, LPG and other petroleum products) in the US market, D^{ROW}_{Crude} is the amount of crude oil demanded in the ROW market (for all products), S^{ROW}_{Crude} is the amount of crude oil supplied by the ROW, and S^{US}_{Crude} is the amount of crude oil supplied by the US.[23]

Differentiating this equation with respect to the price of crude oil and solving for the elasticity of excess supply facing US gasoline producers, η_R, we have:

$$\begin{aligned} \eta_R = \eta^{ROW}_{S,Crude}\left(\frac{S^{ROW}_{Crude}}{D^{US}_{Gas}}\right) + \eta^{US}_{S,Crude}\left(\frac{S^{US}_{Crude}}{D^{US}_{Gas}}\right) \\ - \eta^{ROW}_{D,Crude}\left(\frac{D^{ROW}_{Crude}}{D^{US}_{Gas}}\right) - \eta^{US}_{D,Dist}\left(\frac{D^{US}_{Dist}}{D^{US}_{Gas}}\right) - \eta^{US}_{D,Other}\left(\frac{D^{US}_{Other}}{D^{US}_{Gas}}\right). \end{aligned} \tag{C.4.5}$$

To calibrate η_R using (C.4.5) we use data for 2003 quantities from the EIA's *International Energy Statistics*. The quantities for each of these components of the crude oil market, following the decomposition above, as well as the shares of each component to the quantity of crude demanded for gasoline in the US is reported in the first two columns of Table C.12. In 2003, total world crude considered in our framework is 4,545.8 billion liters (28,954 million

[22] Separating US demand for crude products in this manner is a definitional assumption only. As discussed in the next section, the excess supply elasticity faced by US gasoline producers is calibrated to account for US crude demand for purposes other than gasoline production and should therefore have no impact on the overall adjustments in US or ROW crude oil demand.

[23] We use EIA definitions regarding the quantity of crude oil going to the the production of each petroleum product.

barrels). [24] The rest of the world is the primary supplier of crude oil, contributing 4,046.2 billion liters while the US supplies 499.6 billion liters. On the demand side, ROW crude demand totals 3,419.5 billion liters. US crude oil demand makes up the remainder, with roughly 44% (490.3 billion liters) of total US crude oil demand going to gasoline production.

The final column in Table C.12 reports the central literature values for the elasticities on the right-hand side of (C.4.5) as well as the resulting elasticity of excess supply facing the US gasoline producer (first row), η_R. We use short-run elasticity estimates from the literature because these elasticities are used to quantify the annual response to a change in the yearly average price of crude oil. In this time frame, we can expect both supply and demand adjustments, such as as adjustments in operable crude oil refinery capacity or oil recovery and transportation infrastructure, to be relatively fixed.

We chose elasticities for the US and ROW supply of crude oil of 0.045 and 0.035, respectively. The resulting elasticity of total world crude supply is 0.037 which is consistent with values estimated and used by the literature which range from 0.01 to 0.06 (Krichene, 2002; Smith, 2009; OECD, 2004). Given what appears to be a structural change in this market since at least 1973, we give greater weight to analyses that use more recent data, which appear to suggest smaller elasticities, especially with respect to OPEC sourced crude oil, than in the past. We choose a slightly higher elasticity for US supply than ROW supply; an assumption that is supported by the literature (Ramcharran, 2002; Greene, 2010).

Our value for the elasticity of world crude oil demand, -0.02, is within the range of elasticities found in the literature. Estimates, and values used in the literature, of the elasticity of crude oil demand range from -0.01 and -0.17, with most estimates falling in the range of -0.02 to -0.06 (Krichene, 2002, 2005; OECD, 2004; Gately, 1984; Gately and Huntington, 2002). In our model, the elasticity of ROW crude demand is used to calculate the change in rest of world crude oil use. A number of studies (Gately and Huntington (2002); Dargay and Gately (1995, 2010)) have noted that the demand response for crude products to changes in crude prices, particularly in developed countries, is more limited for price decreases than price increases. Since the RFS will always decrease the price of crude oil, we select a conservative estimate closer to the lower end of the estimates reported in the literature to reflect this asymmetry.

In the absence of comparable short-run estimates for crude demand for distillate fuels and other petroleum products we use an elasticity of -0.02 for each of these components of demand. Since these two components, in addition to total ROW demand for crude oil together make up 90% of total world crude oil demand, it is reasonable to expect that the net elasticity across these components will be very close to the elasticity of world crude demand.

Given our chosen elasticity values and the 2003 quantities of each crude oil market component, we calibrate (16) to reflect an excess supply elasticity for crude oil of 0.5 in our central case. As discussed, there is a broad range of estimates for elasticities of crude oil supply and demand in the literature. To account for this range, we consider values of 0.25 and 0.75 as lower and upper bounds for η_R in sensitivity analysis. One possible way to think about these bounds, would be to proportionally scale the corresponding elasticities for

[24] Our estimate here is slightly below (138 million barrels) the EIA estimate of total world crude consumption because we ignore gasoline used for non-transportation purposes in the US. Keeping the market shares constant, we adjust the total size of the crude market to reflect this difference. As a result, the quantities reported in Table C.12 will be slightly below the values reported by the EIA.

rest-of-world demand and supply of crude oil. For example, when we impose an elasticity of excess supply elasticity of 0.75 the elasticity of rest of world crude crude oil demand of is now -0.03.

Two considerations are important for comparing our crude oil elasticities to other biofuel studies. First, our model measures the annual impact of the RFS on greenhouse gas emissions and we therefore use short run elasticities for crude oil supply and demand. Our elasticities should, and do, differ from those used by studies that analyze the aggregate impact of the RFS over many years and therefore use medium to long run elasticities (Rajagopal et al., 2011; Thompson et al., 2011). Second, the elasticities we specify are for the supply and demand of crude oil and should not be directly compared to the elasticities of gasoline supply and demand used elsewhere (Chen and Khanna, 2012; Drabik and de Gorter, 2011).

C.4.1 Intertemporal Dynamics

The numerical model generates a time path of economic outcomes at one year intervals between 2009 and 2015. To account for underlying dynamic trends that alter our emissions calculations, we allow for domestic and international income, average fuel economy, crop yields, average crude oil prices, and ethanol production technology to adjust exogenously.

We assume that household income grows at an annual rate of 1%. International income growth is modeled through increased world demand for US crop exports. Following historical average annual growth in crop exports over the years 2000-2009, we allow exports to grow by 1.13%, 2.70%, 0.21%, and 1.65% for corn, soybeans, wheat, and cotton, respectively.[25]

We allow fuel economy to exogenously increase by 0.22% per year. This trend is based on fuel economy projections from the 2002 National Research Council analysis of CAFE standards (Council, 2002) and vehicle fleet composition from (Bento et al., 2009).

The price of crude oil generally follows the Reference Scenario projections of AEO 2010, increasing monotonically from \$0.40 per liter (\$63.37 per barrel) in 2009 to \$0.47 per liter (\$73.85 per barrel) in 2015 (in constant 2003\$). Given the sharp spike in crude oil prices in 2008, followed by the precipitous decline in 2009, we take the average of the two prices as our 2009 crude oil price. To capture the strictly positive nature of crude prices in the AEO 2010, we linearly project crude oil prices between 2010 and 2012. For the years 2013 to 2015 we simply use the values taken directly from the AEO 2010 (adjusted to constant 2003\$). Note, in generating our counterfactual baseline this is the price path that we impose exogenously. However, when we simulate the impact of the RFS, the price of crude oil is allowed to endogenously adjust from this initial level, according to (C.3.8).

In 2009 baseline crop yields match observed average US yields taken from NASS. For the years 2010-2015, yields for all crops except hay follow 2010 USDA *Agricultural Projections to 2019*. Hay yields are allowed to increase by the average annual growth rate between the years 1990-2008, or 0.24% per year. CRP rental rates increase by 2% a year, matching historic trends reported in the CRPS. Improvements in international crop yields also follow 2010 Agricultural Projections.

We allow ethanol production technology to improve following US EPA projections (EPA, 2010). We allow the labor requirements of ethanol production to fall by roughly 50% between 2003 and 2015. These improvements are driven by increasing energy efficiency of ethanol

[25] Calculated using data from the USDA's Foreign Agricultural Service (FSA) *Production, Supply and Distribution Online* (PSD) dataset.

production due to a projected expansion in efficient dry mill ethanol production (EPA, 2010). The corn-to-ethanol conversion ratio also improves. In 2015, the average ethanol conversion efficiency is 0.42 liters/kg, which is 6% higher than the 2003 value.

Projections for baseline total crude oil consumption in the rest of the world are from the *International Energy Outlook 2009 Reference Case* (IEO). The IEO provides estimates for 2005 and 2006 and projections for 2010 and 2015. We linearly interpolate values of the years between the reported values. To calculate total petroleum consumption in the rest of the world we take the difference between world consumption and US consumption. The IEO projections do not break down total liquids consumed by type (gasoline, distillates, other). Therefore, we assume that the ratio of each petroleum type to total petroleum consumption is fixed at its 2003 value from 2003 to 2015. We calculate the 2003 shares using data from the EIA's *International Energy Statistics*. This assumption is based on historic trends, which show that the shares of total crude consumption of each crude product are close to fixed. Between 2003 and 2007, the share of total crude consumption for any crude product changed by no more than 1% in the rest of the world.

The Cellulosic Loophole in EISA 2007

According to the federal law (specifically CAA section 211(o)(7)(D)(i)), as adjusted by EISA 2007, the "EPA is required to make a determination each year regarding whether the required volumes of cellulosic biofuel for the following year can be produced. For any calendar year for which the projected volume of cellulosic biofuel production is less than the minimum required volume, the projected volume becomes the basis for the cellulosic biofuel standard [our emphasis]. In such a case, the statute also indicates that EPA may also lower the required volumes for advanced biofuel and total renewable fuel (40 FR 14669 (2010-03-26))."

In effect, this "Cellulosic Loophole" allows the EPA administrator to revise the cellulosic mandates specified in EISA 2007 to the amount of cellulosic ethanol that is anticipated to be in production in the following year when specifying the annual Final Rules regarding the RFS. This loophole has been exercised repeatedly for all of the year's in which EISA 2007 has mandated significant quantities of cellulosic ethanol. In the 2010 Final Rule of the RFS, the EPA revised down the statutory requirement of 100 million gallons to a cellulosic mandate of 5.04 million gallons, or 93% lower than the amount specified under EISA 2007 (pg. 14718, 40 FR 14669 (2010-03-26)). The 2011 Final Rule, revised down the statutory requirement of 250 million gallons to a cellulosic mandate of 6.6 million gallons, or 97% lower than the statutory requirement (Table I.D.1, 40 FR 76790 (2010-12-09)). In the 2012 Final Rule, the EPA revised down the statutory requirement of 500 million gallons to a cellulosic mandate of 8.65 million gallons, or 98% lower than the statutory requirement (Table I.A.3-1, 40 FR 1320 (2012-01-09)).

C.5 Model Validation

Comparison of Out of Sample Model Predictions to Historic Data

We calibrate the model to 2003 so we are able to compare our model's predictions against several years of observed data for which the RFS was largely considered to be non-binding. Table C.9 presents our out-of-sample model predictions averaged over the years 2004-2009 against observed data over that period.[26] Data for individual model years generally are similar to those reported here, with the caveat that, since we do not explicitly model commodity stocks in our model, our model predictions are smoother than those observed. Observed data is more variable, since various exogenous factors impact the amount of commodities stored or drawn down in a given year, such as droughts in individual commodity markets (for instance, wheat in 2007-2008), or interactions with other exogenous price swings elsewhere in the macroeconomy.

For corn, our model predictions are on average off by -1.78%, which suggests a good level of fit. Likewise, soybeans, wheat, and CRP predictions are off by similar margins. Hay exhibits slightly more error, at 5.88%, which likely reflects the fact that hay is the slack land-use in our model, but also because small deviations in observed hay yields magnify deviations relative to our model predictions. Cotton is off even more, with average deviations of -14.75%, although this is amplified by the fact that the base for cotton is orders of magnitude smaller than that for other crops. Our corn ethanol predictions are slightly higher, 8.62% greater, than that observed over this period, although in magnitude terms, we are off by slightly less than half a billion gallons for a given year.

Figure C.1 plots a two-year moving average of our measure of CRP land (General signup plus Continuous, Non-CREP signup) against the commodity price index for price received (pegged to 1990 -1992). Starting in 2007 and continuing through 2008, commodity prices started undergoing a considerable structural change. The commodity price index for prices received grew from a moving-average value of roughly 115 in 2006 to roughly 143 in 2008, denotes growth in average prices received of roughly 24%. By 2010 this sloughs off slightly to an index value of 136, which still denotes an increase in the average commodity price level relative to 2006 of roughly 19%. Not surprisingly, our measure of CRP starts to decline in 2008, resulting in a shedding of 2.33 million hectares between 2008 and 2010, given the data reported in Table C.11. Relative to the 2003 total, this is a reduction of 17.2%—a non-negligible reduction in CRP acres over this period.

For sake of comparison, our model finds a 0.2 million hectares or roughly half a million acre fall in CRP due to the RFS in 2012 when the VEETC is continued (see Table C.11). This is internally consistent with the CRP acreage elasticity of -0.07 (as reported in Table C.1, given the change in the returns to cropland arising due to the change in the RFS. In this year our model predicts the RFS will bind by 6.1 billion liters (see Table 3.1), requiring an additional 1.1 million hectares of corn land devoted to ethanol production (see Table C.11). This implies a fall in CRP acres of 0.03 hectares for every 1,000 liters of ethanol added by the RFS, relative to an increase in corn hectares devoted to ethanol production of 0.18 hectares per 1,000 liters. We believe our model's prediction for this fall in CRP is conservative and reasonable. Further, it is fully consistent with observed changes in CRP acreages reported in recent years. Between 2008 and 2009 corn ethanol expanded by 2.4 billion liters and corn acreage expanded by 0.28 million hectares, whereas CRP acreage fell by 0.38 million hectares.

[26]Data for individual model years are available from the authors by request.

Comparison of Out of Sample Model Predictions to 2006-2009 Average of USDA Long-Term Projections

Table C.10 compares our model predictions against an average of the USDA's Long-Term Projections for the years 2006, 2007, 2008, and 2009. We compare vis-a-vis an average of Long-Term Projections, given the large degree of variation in the projections over this time period, owing to the considerable changes in commodity markets observed in these years and changes in the assumptions underlying the USDA estimates, in particular prior to the EISA 2007 being fully embedded into their projections.[27] In general, our estimates are largely consistent with the USDA Long-Term Projections.

C.6 Calculation of GHG Emissions

We calculate greenhouse gas emissions following the equation for emissions provided in Bento et al. (2013b). As reported there, greenhouse gas emissions (GHG) are given by:

$$GHG = \phi_P P + \phi_E E + \phi_Y A_Y + \phi_Z A_Z + \phi_{N,D} A_N^D + \phi_{N,W} A_N^W + \phi_R R^W \tag{C.6.1}$$

where ϕ_i are GHG emissions released per unit of good or activity i (where i spans the economic sectors previously enumerated), and all quantities and emissions factors are specific to country D unless otherwise indexed.[28] We use a slightly simpler notation to describe the damages from GHG emissions in the main text of the paper. As discussed in Section 3.3.1, GHG in C.6.1 is a function of $\frac{\bar{E}}{\bar{F}}$, which is equal to θ when the RFS is binding. It is also a function of the total amount of fuel, $\bar{F}$,[29], which is itself a function of θ. In addition, in equilibrium $A_Y(\theta)$, $A_Z(\theta)$, $A_N^D(\theta)$, and $A_N^W(\theta)$. What follows is a complete discussion of the emissions factors used in our analysis.

Overview

The emissions coefficient for gasoline, ϕ_P, is inclusive of the emissions from both gasoline consumption and production. In contrast, we consider only the emissions from ethanol production, $\phi_{E,M}$, given that the carbon stored in ethanol, and released during ethanol combustion, is absorbed from the atmosphere during the growth of corn (IPCC, 2007). The agricultural production emissions coefficients, ϕ_Y and ϕ_Z, include emissions from the production of agricultural inputs, such as fertilizer, as well as on-farm emissions.[30] All of these emission coefficients, as well as the coefficient on crude oil, ϕ_R, are positive, reflecting the fact that these activities generate GHG emissions. In contrast, the emissions coefficients

[27] Hay and CRP are not reported here since the USDA Long-Term Projections do not include projections for hay or land held in the CRP.

[28] While marginal emissions coefficient for gasoline is inclusive of the emissions from both gasoline consumption and production, we consider only the emissions from ethanol production because the carbon stored in ethanol and released during ethanol combustion, is absorbed from the atmosphere during the growth of corn (IPCC, 2007).

[29] Given C.3, we note that $P = \alpha_{PF}\bar{F}$, $E = \theta\bar{F}$, and $R^W = R^P = \alpha_{RP}P = \alpha_{RP}\alpha_{PF}\bar{F}$ where α_{PF} and α_{RP} are the per-unit conditional factor demands of gasoline in blended fuel, and crude oil in gasoline, respectively.

[30] These are emissions that arise from interactions between agricultural soils and farm inputs and fossil fuel combustion.

of non-agricultural land uses, $\phi_{N,k}$, are negative, reflecting the annual emissions benefits from the uptake of atmospheric carbon by biomass (such as the growth of forest or grasslands) and through increased carbon sequestration in soils (Fargione et al., 2008). These benefits are lost when non-agricultural land is brought into agricultural production. The carbon benefits of non-agricultural land differ between the two countries, because the carbon stocks of CRP are limited because these lands have historically been cleared for agricultural production, and tend to be held as grasslands, while it is likely that expanded agricultural production in the rest of the world will take place at the expense of previously undisturbed lands with much larger carbon stocks, such as forests or shrubland (see for example EPA (2010) Searchinger et al. (2008) and Fargione et al. (2008)).

Gasoline

The lifecycle emissions of gasoline, ϕ_P, are 3.0 kgCO_2e/liter, which is the baseline lifecycle emissions for US gasoline estimated by NETL (2008). This factor is used by the EPA in the Regulatory Impact Analysis of the RFS, as well as the RFS Final Rule, and includes emissions from crude oil extraction, transport and refining, the transportation and distribution of finished gasoline, and tailpipe emissions (NETL, 2008).

Ethanol Production and Combustion

The lifecycle emissions from ethanol production are assumed to be 0.6 kgCO_2e/liter. This factor assumes a representative natural gas fired dry-mill ethanol plant, consistent with the US (EPA, 2010). We also account for the release of CH_4 and N_2O from ethanol combustion, which totals 0.02 kgCO_2e/liter (EPA, 2010).[31] Combining, ϕ_E is 0.62 kgCO_2e/liter.

We consider only natural gas fired ethanol production for our emissions analysis because the construction of additional coal fired ethanol production facilities is likely to be limited by the RFS legislation, because ethanol produced by these facilities is unlikely to achieve the 20% lifecycle emissions reduction threshold (EPA, 2010). While we do account for the make up of US ethanol production in the economic model, for our emissions analysis we consider the "marginal" or additional production of ethanol, which we assume occurs in natural gas fired dry mills. Our ethanol production emissions factor is notably lower than an US average emissions factor for ethanol production because coal fired ethanol production is not considered in our emissions analysis.

Agricultural Production

To construct ϕ_Y and ϕ_Z we consider on-farm sources of emissions, which include agricultural N_2O and emissions from energy use and liming, as well as emissions from agricultural input production. In our central case, N_2O emissions from agricultural production are calculated using methods and default parameters from the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). These methods map nitrogen additions to agricultural soils, from synthetic fertilizers and crop residues, to N_2O emissions.[32] Crop specific synthetic fertilizer application rates are from our agricultural dataset. Nitrogen additions from crop

[31]While the CO_2 released during ethanol combustion is completely offset by carbon uptake during the growing of corn, this is not the case for other greenhouse gases.

[32]The IPCC methods also consider N inputs from organic fertilizer and sewer sludge. In the US, nitrogen inputs, and therefore N_2O emissions, from organic fertilizer and sewer sludge are small and are therefore not considered (EPA, 2009).

residues are calculated using the crop yields from the economic model and crop-specific IPCC default parameters (IPCC, 2006).

Using the IPCC methods, the production of corn is more than twice as emissions intensive than each of the other crops and six times more emissions intensive than soybeans. Although the quantity of nitrogen additions is a major factor in quantifying N_2O emissions from agricultural production, other factors such as soil characteristics, previous crop, cropping practices and weather patterns can have a significant effect. As such, there is no agreed upon method for translating nitrogen additions to N_2O emissions.[33] To account for these uncertainties, as sensitivity analysis we adjust the agricultural emissions factors to reflect alternative methods for assessing N_2O emissions from agricultural production. For our low case, we use crop-specific N_2O emissions factors consistent with the US average of DAYCENT/CENTURY simulations used by the EPA (2010). Relative to the central case, emissions from soybean production are three times greater in low agricultural N_2O case.[34] In the high case, we use the upper bound recommendation of Crutzen et al. (2008) and assume 5% of nitrogen in nitrogenous fertilizer is converted to N_2O.

Emissions from agricultural energy use are calculated using the crop specific energy input requirements from our agricultural data set and lifecycle emissions factors for the agricultural use of each energy type estimated using GREET 1.8c (Wang, 2009). These factors include both emissions from the combustion of the fossil fuel plus the emissions from the production and transportation of the fuel. Emissions from lime application to agricultural soils are estimated using IPCC default methods which assume that all carbon in lime applied to agricultural soils is converted CO_2 (IPCC, 2006).

We use GREET 1.8c (Wang, 2009) to estimate the lifecycle emissions of producing nitrogenous (N), phosphate (P), and potassium (K) fertilizers, pesticide and agricultural lime. The farm input production lifecycle includes feedstock recovery and transportation, and the production and transportation of the final farm input.

The emissions from nitrogen production are 2.99 kgCO_2e per kilogram nutrient N. This factor is estimated assuming a US average nitrogen fertilizer mix of 70.7% ammonia, 21.1% urea and 8.2% ammonium nitrate, which is based on USDA data. This emissions factor includes the emissions from producing the feedstock to fertilizer production (primarily natural gas) as well as the emissions from the production and transportation of the fertilizer itself. We use an emissions factor for the production of phosphate fertilizer of 1.04 kgCO_2e per kg nutrient P. This factor includes the production, processing and transportation of sulfuric acid, phosphoric rock and phosphoric acid. Our emissions factor for the production of potassium fertilizer, which includes only the emissions from production and transportation of potassium oxide (K_2O), is 0.69 kgCO_2e/kg nutrient K. The lifecycle emissions of agricultural lime production are 0.63 kgCO_2e/kg lime and present the net emissions from mining,

[33] For example, Crutzen et al. (2008) suggest that between 3-5% of the N in nitrogen additions to soil would be released as N_2O rather than the IPCC default of 1%. Crutzen et al. also find that total N_2O emissions calculated using the IPCC methods are consistent with their own analysis if all sources of N_2O emissions are considered, particularly livestock production and grazing.

[34] We refer to this as our low sensitivity case because it results in the RFS having a smaller net impact on agricultural emissions. This is primarily due to the increased emissions savings due to displaced soybean production. N_2O emissions from soybeans are substantially higher in the low emissions case because the DAYCENT/CENTURY models account for the nitrogen fixed by leguminous plants (soybeans).

production and transportation. The emissions factor for the production of pesticide, 21.9 kgCO_2e/kg pesticide, represents the weighted average emissions from the production of four herbicides and a general insecticide.[35]

Domestic Land Use Change

We assume that the emissions from converting land held in CRP to cropland, $\phi_{N,D}$, are 2.3 mgCO_2e/ha. To calculate this factor we assume, following the EPA (2010), that the conversion of CRP land to cropland results in the immediate release of all carbon stored in the above-ground biomass on CRP land. In addition, the carbon stored in below-ground biomass and soils of CRP land is released within the next 30 years. Consistent with standard practice (see EPA (2010)), we amortize total emissions from land use conversion over 30 years, with no discounting.[36] We assume that CRP land is abandoned cropland planted to perennial grasses for 15 years (prior to conversion), having stored 30.51 mgCO_2e/ha in above and below ground biomass and 37.95 mgCO_2e/ha in soils (Fargione et al., 2008). We focus on the conversion of grasslands to cropland because while biomass on CRP land can take a number of different forms, in 2007 at least 77% of continuous signup CPR was classified as native or introduced grasses (FSA). Also, given the costs of converting forested land to cropland, it is CRP held in grassland that will likely be converted to cropland. If CRP lands converted to production sustained another type of land cover, for example native grasses or woody biomass, then the emissions consequences of conversion could be markedly higher (Fargione et al., 2008). On the other hand, the CRP targets marginal cropland with specific environmental benefits. If the land in CRP frequently moved in and out of agricultural production, or is degraded, the soils may have accumulated little soil carbon, and the emissions from converting the land back to cropland would be lower than our central estimate.

World Land Use Change

As a central value, we assume that the emissions benefits lost as a result of the expansion of non-US cropland, $\phi_{N,W}$, are 8.0 mgCO_2e/ha (EPA, 2010). The emissions from world land use change are substantially larger than the emissions from domestic land use change. This is because cropland expansion in the rest of the world is predicted to displace previously undisturbed land cover with large carbon stocks. The international land use change emissions factors are derived from economic models used by the US EPA that predict the location (54 regions) and type (pasture, native ecosystems) of land converted to cropland as a result of the RFS for corn ethanol (EPA, 2010).[37] The economic results are further dis-

[35] Crop specific shares of herbicide and insecticide to total pesticide are calculated from the ARMS. For each crop, the share of herbicide is greater than 90%. We use the GREET 1.8c assumptions for the herbicide mix applied to corn and soybeans, and assume herbicide applied to hay, wheat and cotton consists of equal parts of the four herbicides.

[36] The 30 year time frame is justified because this represents the average lifespan of an ethanol production facility. However, other studies have relied on different amortization assumptions. For example, Searchinger et al. (2008) use a 15 year time period.

[37] The EPA assessment of the RFS (EPA, 2010) also allows for cropland to expand onto pasture land. To the extent that the amount of land held as pasture falls in response to biofuel policy (due to reduced livestock production), this pathway of adjustment serves to mitigate the conversion of native ecosystems to agriculture, and therefore greenhouse gas emissions.

aggregated spatially and into twelve land conversion categories, including forest, grassland, shrubland and savanna among others. Land use conversion patterns are estimated using historical satellite land use cover data. There is considerable heterogeneity in the greenhouse gas emissions consequences of converting different native ecosystems to cropland because of the variability in carbon stored by different ecosystem types. For example, tropical forests, on average, have larger carbon stocks than temperate forests or grasslands, and as a result, tropical deforestation releases relatively more greenhouse gases than the conversion of temperate forests or grasslands.

International Crude Oil Consumption

To calculate emissions related to changes in rest of world crude oil consumption, we account only for the emissions from changes in crude used to produce gasoline and distillate fuels, and exclude changes emissions from crude going to other crude products (here defined as including residual fuel oils, jet fuel, LPG and other miscellaneous products). We are therefore considering emissions from approximately 47% of the world crude oil market.[38] Excluding emissions from other crude products is a conservative assumption that allows us to isolate adjustments in rest-of-world crude oil consumption related to the transportation sector that are most likely to have first-order implications for changes in greenhouse gas emissions resulting from the RFS. This assumption is discussed in greater detail in Bento et al. (2013b).

Crude Oil Emissions Factors

To calculate the emissions from rest-of-world crude oil consumption, we account for changes to each component of the world market for crude oil separately (as discussed above) using fuel specific emissions factors from the EIA's *Voluntary Reporting of Greenhouse Gases Program*. These emissions factors capture only the direct release of CO_2 from the combustion of petroleum fuels, not the emissions resulting from the refining of crude oil into the final products.

In our central case, where we account for emissions only for changes in crude used for gasoline and distillate fuels, the average emissions factor for rest of world crude consumption is 2.6 $kgCO_2e$/liter (408 $kgCO_2e$/barrel). This represents the emissions per liter of distillate fuels and motor gasoline weighted by the rest-of-world market shares of these fuels in 2003. The market shares for gasoline (32%) and distillate fuels (68%) are calculated using data from the EIA's International Energy Statistics. The emissions factor for crude used for gasoline production in the rest of the world is 2.4 $kgCO_2e$/liter (374.2 $kgCO_2e$/barrel). The emissions factor for distillate fuels is slightly higher 2.7 $kgCO_2e$/liter (426.3 $kgCO_2e$/barrel).

We back out these emissions factors from the EIA *International Energy Statistics* reported total CO_2 emissions from petroleum production in 2003. First, for both the US and ROW we deduct from total 2003 CO_2 emissions, the CO_2 emissions from gasoline and distillate consumption calculated using the emissions factors described above and the 2003 quantities of gasoline and distillate consumption reported by the EIA. We then divide these quantities of CO_2 by the quantity of petroleum that we categorize as other crude products. This provides emissions per unit of other petroleum products in both the US and ROW.

[38]In 2003, total crude used for purposes other than US gasoline production totalled 4,055 billion liters. Of this, US distillates totaled 5.5% while ROW gasoline and distillates totalled 16.2% and 25% respectively.

The difficulty in calculating emissions factors for our category of other crude products lies in assigning a level of emissions to the EIA defined other petroleum products, since this petroleum may not be combusted, but rather used as a manufacturing input or lubricant. Our method of deriving an emissions factor for our category of other crude products implicitly uses EIA assumptions regarding the composition of crude products in this category and their resulting emissions. That the emissions factors for the other crude category are lower than the emissions factors for gasoline or distillates is reasonable, given that the EIA defined category of other crude is not necessarily combusted. In addition, our category of other crude oil products is made up of a large share of LPG (29.4% in US, 18.1% in ROW) which has an emissions factor that is 40% lower than that of gasoline or distillates (1.5 kgCO_2e/liter).

C.7 Calculation of Change in Trade Balance

Table C.13 reports the crop prices, crude oil prices, and import and export quantities used to compute the change in the trade balance due to the RFS.

Corn, Soybean, and Wheat Exports

The change in the trade balance for corn, soybean, and wheat exports comes directly from the model, since these quantities are tracked explicitly in the model, given (C.3.7) as discussed in Section C.3.

Cotton Exports

The change in the trade balance for cotton is a function of the change in cotton prices and $NX^{ROW}_{i=5}$ as discussed in Section C.4. Given the elasticities and shares reported there this quantity emerges given simple algebra and given the equilibrium prices and quantities.

Crude Oil Imports

The change in the trade balance for crude oil is a function of the change in the price of crude oil and imports of crude oil from the ROW to the US, $S^{ROW}_{Crude} - D^{ROW}_{Crude}$ as discussed in Section C.4. Given the elasticities and shares reported there these quantities emerge given simple algebra and given the equilibrium prices and quantities.

C.8 External Benefits Calibration and Discussion

External Benefit Parameters

Our calculation of MD^{GHG} assumes a central price of carbon of \$25.00 per ton Carbon equivalent (ton Ce), and a lower and upper bound estimate of \$0.70 per ton Ce and \$100.00 per ton Ce, respectively. Our central estimate of MD^M_{LP} is \$0.010 per mile, with lower and upper bounds of \$0.004 and \$0.100 per mile, respectively. For MD^M_A we assume central, lower, upper values of \$0.0350, \$0.0140, and \$0.0875 per mile, respectively. For MD^M_C, we assume values of \$0.015, \$0.035, and \$0.090, for the low, central, and high cases, respectively. All of these reflect the central, lower, and upper bounds of Parry and Small (2005), with a few exceptions. Our central estimate of MD^M_{LP} has been updated using the values reported in Small and Verhoef (2007), and our central estimate of MD^M_A has been updated to reflect the latest value of statistical life figures from the USDOT, as reported in Parry et al. (2010).[39] MEB^N reflects the sum of the various external benefits provided by land held in CRP, including the recreational, soil quality, air quality, and GHG mitigation benefits. We assume central, low, and high values for these benefits of \$52.90, \$13.22, and \$92.57 per acre of land held in CRP, respectively. Since these values represent the sum of specific classes of external benefits, and most studies only provide estimates with respect to a subset of the external benefits we consider here, we leave a full discussion of the literature estimates that generated these bounds for the Appendix.

Our estimate of the oil security premium, MEC^P, reflects the price volatility, monopsony, and national security costs of oil dependency as discussed above. With regard to price volatility, we assume a central value closer to the zero end of Leiby et al. (1997) (as updated by Parry et al. (2007)), of \$0.03 per gallon of gasoline, assuming that the private sector internalizes 90% of the risk of price shocks. For the lower and upper bound estimates we adopt the updated minimum and maximum values of \$0.00 and \$0.20 per gallon, respectively. With regard to monopsony, we assume a central value for these costs of \$0.10 per gallon of gasoline, and lower and upper bound estimates of \$0.07 and \$0.24 per gallon, respectively (originally from Leiby et al. (1997) but as updated by Parry et al. (2007)). For national security, we assume a central, lower, and upper values of \$0.09, \$0.03, and \$0.15 per gallon of gasoline, respectively. The lower and upper bounds reflect the range of costs reported in Delucchi and Murphy (2008), with the central estimate the simple mean of these bounds. Summing across these three components, implies central, low, and high estimates of the oil security premium, MEC^P, of \$0.22, \$0.10, and \$0.59 per gallon of gasoline, respectively.[40]

[39] The low and high values in this case have also been adjusted by dividing (multiplying) the central value by 2.5 for the low (high) case, following Parry and Small (2005).

[40] Excluding the national security component, which most literature estimates do not include, implies central, lower, and upper values of our oil premium \$0.13, \$0.07, and \$0.44 per gallon, respectively. This compares to \$0.31, \$0.15, and \$0.53 per gallon for central, lower, and upper values reported in Leiby (2007); \$0.09, \$0.06, and \$0.13 per gallon for central, lower and upper values reported in Leiby et al. (1997) (as cited in Leiby (2007), adjusted to 2003\$); central, lower, and upper values of \$0.12, \$0, and \$0.33 per gallon as reported in Parry and Darmstadter (2003), and central, lower, and upper values of \$0.12, \$0.08, and \$0.50 per gallon as reported in Parry et al. (2007). With respect to Parry et al. (2007), the central estimate of \$0.12 per gallon is the level recommended by a NRC (2002) review by experts, and the range reported is inclusive of national security costs, citing the earlier study by Delucchi and Murphy (1996) which reported values from \$0.01 to \$0.06 per gallon for these costs. EPA (2010) uses the Oil Security Metrics Model developed by Greene and Leiby at Oak Ridge National Labs, which builds on Leiby (2007). Incorporating comments from peer reviewers to Leiby (2007) and using the 2007 EIA Annual Energy Outlook, EPA (2010) reports central, low, and high estimates of \$0.26, \$0.15, and \$0.40 (adjusted to 2003\$) per gallon, respectively. When they update the analysis to reflect the 2009 EIA Annual Energy Outlook for year 2025, they report central, low, and high estimates of \$0.42, \$0.24, and \$0.64 per gallon, respectively. Table 2 in Leiby (2007) reports the major changes in the 2007 update relative to Leiby et al. (1997); larger US GDP, higher US oil imports, larger world crude oil prices, and increased likelihood of oil supply disruption are the main drivers for the increased numbers with a larger SPR and more elastic US import demand offsetting some of this increase. At \$0.22 per gallon our central estimate (which includes a central estimate of costs from national security of \$0.09 per gallon) is well within the range of more recent central estimates that exclude national security costs, \$0.12 per gallon as reported in Parry and Darmstadter (2003); Parry et al. (2007) and \$0.26–\$0.42 per gallon as reported in EPA (2010).

Monte Carlo Sampling

We use Monte Carlo methods to quantify uncertainty with respect to our welfare analysis. To do this, we estimate a separate independent gamma distribution[41] for MEC^{GHG} (cost of Carbon), MEC^{P}, MEB^{N}, MD^{M}_{LP}, MD^{M}_{A}, and MD^{M}_{C} by choosing parameters for these distributions such that the lower, central, and upper bounds for these parameters taken from the literature match the 10^{th}, 50^{th}, and 90^{th} percentiles for each respective gamma distribution. When reporting the Monte Carlo results below, we report the median[42] value across 2000 random draws, as well as the 90% confidence interval.

Additional Discussion of External Benefits Considered

External Costs of Oil Dependency

What we refer to as the 'oil premium' is the marginal external costs of oil dependency, expressed in $ per gallon of gasoline consumed in the US.[43] Formally, this is the difference between the costs to the US economy as a whole from oil consumption and those private costs incurred by individuals and firms (Parry and Darmstadter, 2003). Prior literature has emphasized two main channels of external costs, the monopsony and volatility costs, but a third, national security expenditures, is also worth discussing in the context of large-scale policies such as the RFS.[44]

First, the 'monopsony' component of the oil premium is due to the fact that, since the US is a sufficiently large purchaser of foreign oil supplies, its purchases can affect the world price of crude oil.[45] Since individual consumers only account for the market price of oil when making decisions and not the marginal purchasing power of importers (e.g. refiners) as a

[41] We choose the gamma distribution since it permits non-negative values and is a flexible specification. In addition, the gamma is skewed to the right so it places a tighter bound on lower or more conservative estimates, while permitting a wider range of estimates in the upper range. It appears to be commonly used in other Monte Carlo analyses; see for example Parry and Small (2005).

[42] We report median estimates here since estimates drawn from the extreme tails (across the several independent gamma distributions) can lead to estimates of the mean that are less reflective of the central tendency.

[43] While the native units for this calculation are $ per barrel of crude oil, we convert our estimates to a per gallon measure, consistent with Parry et al. (2007).

[44] Some also include the costs of OPEC oligopoly power as an additional oil dependency market failure (Kaufmann et al., 2004; Greene and Ahmad, 2005). Greene and Ahmad (2005) posit three key channels through which monopoly power generates external costs: 1. excessive transfers to monopolist producers; 2. loss of potential GDP due to higher prices inducing artificial 'economic scarcity' and suppressing economic output, and 3. additional adjustment costs (see below). The literature on the presence of oligopoly power in the world crude oil market is mixed. Leiby (2007) summarizes the debate regarding OPEC's market power, stating that "OPEC remains able to exercise some degree of control over the response of world oil supplies to variation in world oil prices." Recent work by Bremond et al. (2012) performs several cointegration and Granger causality tests to evaluate whether OPEC exhibited oligopoly power over five time periods spanning 1973 to 2009. They reject the null-hypothesis of no causality between prices and production with respect to OPEC producers, for the periods 1993 to 2000 and 2001 to 2009 (Appendix Table A3). In this case, evidence of a causal linkage between prices and production implies that OPEC responds to market prices, and are therefore price-takers and hence, not acting as a monopolist. Similar tests of a production-price relationship, however, fail to reject the null in all periods.

[45] The fact that the US is a monopsonist in this market implies that when it reduces its demand for crude oil, as would be the case for a binding RFS, it also causes the world price of crude oil to fall at the margin. In turn, this decreases the total amount that the US pays for crude oil (both marginal and inframarginal).

group on lowering the world price of crude oil, this implies a transfer that constitutes an additional cost savings from reducing oil consumption. This monopsony premium depends upon the gap between domestic consumption and the domestic supply of crude oil, the elasticity of total world supply of crude oil, as well as the strategic power of OPEC to act as a monopolist (Leiby, 2007; Parry and Darmstadter, 2003). Note, however, that since the market for crude oil is a truly global market it is not a function of US crude imports directly.

Second, the 'volatility' component of the oil premium consists of the economic disruption costs that are incurred in the world crude oil market as a result of unanticipated economic shocks. Costs from this component emerge from two channels: import costs and macroeconomic adjustment costs.

Import costs constitute a wealth transfer from domestic consumers to foreign suppliers as a result of unanticipated price shocks. Import costs are only external to the market economy to the extent that businesses and households incorrectly anticipate the risk of price shocks, and/or lack adequate insurance mechanisms and futures markets for hedging risk. Thus, only this portion of import costs should be accounted for when computing costs from this channel. Estimates of this portion of the volatility premium require first determining the expected price increase from a shock,[46] and secondly, determining the portion of this expected price increase that is anticipated by individuals and businesses, i.e. already accounted for by the market economy.[47] With respect to the latter, empirical estimates are lacking, but analysts typically consider that between 25% and 100% of this import cost channel is anticipated.[48]

Macroeconomic adjustment costs are those costs that are borne by downstream consumers of crude products and upstream suppliers of crude oil that result due to the fact that neither can immediately adjust to unanticipated shocks. Macroeconomic adjustment costs emerge as a result of variability in the world crude oil price on the expected costs of crude oil consumption. Unlike volatility emerging from agricultural commodities or other natural resource markets which can be internalized by inter-temporal consumption shifting, volatility in crude oil markets generates external costs largely given the fact that crude oil is an intermediate input in production (Parry and Darmstadter, 2003). As a consequence, volatility may impose costs on the economy that upstream suppliers that produce, import, and refine crude oil do not account for as private economic agents. Likewise, volatility also affects downstream end-users of crude products, such as retail gasoline consumers and in-

[46] The expected price increase from a shock is the probability of future price shocks multiplied by the expected average price increase from a shock. Both the probability and average price increase are computed given data on past shocks and the average increase in the world crude oil price incurred during those shocks.

[47] Leiby (2007) also accounts for the impact of the Strategic Petroleum Reserve (SPR) as a mechanism to internalize some of these costs, but assume no change in the SPR from its current size. Parry and Darmstadter (2003) state that "most analysts expect the future frequency and size of disruptions to be lower than in the past, though there is little agreement on how much lower." We use values that account for these assumptions in our simulations. However, it is not clear the extent to which the increase in the frequency of extreme weather events such as hurricanes has impacted this assessment in recent years. The extent that global climate change is a determinant of these events is widely speculated upon, but remains largely unknown. While we do not adjust our central values to reflect ambiguity along this dimension, it is possible that policymakers do.

[48] To our knowledge, empirical estimates of how much of these costs are anticipated simply do not exist (see Parry and Darmstadter (2003)). Consequently, note that under 100% anticipation, this channel implies zero costs and thus has no impact on the oil price premium.

dustry, given the presence of sunk capital investments—automobiles for the case of retail gasoline consumers, and plant and machinery in the case of industry—implies adjustment costs that are not reflected in the market price for crude oil or crude products.[49] As with import costs, macroeconomic adjustment costs only generate external costs to the extent that firms and individuals cannot perfectly anticipate and/or insure against volatile oil prices. Consequently, how much of these adjustment costs are unanticipated/uninsured is unclear. Macroeconomic adjustment costs are computed assuming a GNP-oil price elasticity (percent change in GDP from a 1 percent change in the crude oil price) and disruption probabilities. Macroeconomic adjustments costs are based on total domestic production, not imports, since the market for crude oil is global. Finally, it appears that macroeconomic adjustment costs appear to be asymmetric—costs of unanticipated oil price increases are greater than the benefits of unanticipated oil price decreases (Parry and Darmstadter, 2003). Unlike import costs, macroeconomic adjustments costs are based on total domestic production, not imports, since the market for crude oil is global. Whether these two channels of costs are actually external costs depends critically on the extent that firms and individuals cannot perfectly anticipate and/or insure against volatile oil prices.

A third component of the oil premium that is much discussed, but generally not included in most estimates (Leiby et al., 1997; Parry and Darmstadter, 2003; Greene and Ahmad, 2005; Leiby, 2007), are the costs of securing the nation's crude oil supplies, including military and diplomatic expenditures from recurring troop and military asset deployment to strategic oil producing regions, one-off costs for wars, as well as the operational costs of running and establishing the Strategic Petroleum Reserve (SPR)[50]—which we collectively refer to as the national security expenditures component of the oil premium. Many analysts do not include this component of costs in their estimate of the oil premium, largely for two reasons. First, it is difficult to attribute what component of national security expenditures comprise spending to secure crude oil supplies.[51] Secondly, many national security expenditures are non-marginal,[52] and so attributing a marginal change in the external costs of national security expenditures from a marginal change in crude oil is not valid since such costs will not vary per unit of crude oil consumed at the margin. Recognizing these limitations, we include estimates of national security expenditures in our measure of the oil premium for two key

[49]For example, for a positive shock households will be stuck with less fuel efficient vehicles or residential heating and cooling systems. While these items can be sold off through market transactions, the decline in value of this stock as a result of the new positive shock regime is unanticipated and thus unaccounted for by individuals at the time of purchase. Likewise, energy-intensive industries will be stuck with capital and labor in more costly production processes or simply stop production altogether, until plants can be re-tooled to more energy efficient production processes (Parry and Darmstadter, 2003).

[50]While the SPR is accounted for when determining the various components of the oil premium in some analyses (Leiby, 2007), the costs of running and establishing the SPR typically are not.

[51]National security deployments and wars have multiple and coterminous objectives that cannot be easily disentangled. Even if one objective was removed from the political calculus, such as the benefits to securing crude oil supplies, it is not possible to say whether the deployment or war would not have taken place anyway.

[52]Nations do not necessarily send fewer troops into a war theater simply because one less objective, such as the benefits from securing crude oil supplies, is not considered. Further, nations do not necessarily send troops in equal proportion, say, to the number of barrels of crude oil likely to affected by the military engagement. Rather, wars are fought and troops and military assets deployed to achieve military victory, given opposing forces and other strategic considerations. Such deployments are fundamentally large-scale and non-marginal.

reasons. First, the RFS is a large-scale policy intended to achieve non-marginal changes in the nation's consumption of crude oil. Secondly, as a part of the Energy Independence and Security Act of 2007, the RFS was established to explicitly address this objective of oil dependency.[53]

Some authors also include the costs of OPEC oligopoly power as an additional oil dependency market failure (Kaufmann et al., 2004; Greene and Ahmad, 2005). Greene and Ahmad (2005) posit three key channels through which monopoly power generates external costs: 1. excessive transfers to monopolist producers; 2. loss of potential GDP due to higher prices inducing artificial 'economic scarcity' and suppressing economic output, and 3. additional adjustment costs (see below). The literature on the presence of oligopoly power in the world crude oil market is mixed. Leiby (2007) summarizes the debate regarding OPEC's market power, stating that "OPEC remains able to exercise some degree of control over the response of world oil supplies to variation in world oil prices." Recent work by Bremond et al. (2012) performs several cointegration and Granger causality tests to evaluate whether OPEC exhibited oligopoly power over five time periods spanning 1973 to 2009. They reject the null-hypothesis of no causality between prices and production with respect to OPEC producers, for the periods 1993 to 2000 and 2001 to 2009 (Appendix Table A3). In this case, evidence of a causal linkage between prices and production implies that OPEC responds to market prices, and are therefore price-takers and hence, not acting as a monopolist. Similar tests of a production-price relationship, however, fail to reject the null in all periods. Consequently, we do not consider this component of costs when computing the oil premium.

External Benefits Provided by Land Set Aside in the CRP

The external benefits provided by land held in the CRP, MEB^N, are assumed to total \$52.90 per acre. We assume a lower bound estimate of benefits \$13.23 (75% below the central estimate) and an upper bound estimate of \$92.58 (75% above the central estimate. This is the sum of the various external benefits provided by land held in CRP. There are several external recreational benefits from land held in the CRP which we discuss in turn.

John (1993) finds an equivalent[54] per acre benefit of wild-life viewing of \$11.25. More recent work by Feather et al. (1999) find a per acre benefit of wild-life viewing of \$10.02, which is the value we assume. John (1993) finds an equivalent value per acre of waterfowl hunting of \$5.15. Young and Osborn (1990) find an equivalent value per acre of small-game hunting of \$13.05. Feather et al. (1999) find a per acre benefit of pheasant hunting of \$2.36/acre. Summing these three hunting benefits we compute a total external benefit from hunting of \$20.56 per acre. Ribaudo (1989) finds an equivalent per acre benefit from sport-fishing alone of \$0.63. Feather et al. (1999) find a per acre benefit of freshwater recreation (inclusive of sport-fishing) of \$1.07, which is the value we assume. The sum total of the external benefits of wild-life viewing, hunting, and freshwater recreation of \$31.65 per acre, constitute the total anthropogenic recreational benefits to CRP land. Given that we do not include land

[53]For those that remain uncomfortable regarding our consideration of this component of the oil premium in our central estimates, we note our total value of the oil premium including all three cost components is well within the range of more recent central estimates of the oil premium that consider just the monopsony and volatility channels, as we discuss in greater detail below.

[54]The use of the term 'equivalent' here is used to denote the conversion of an estimate reported for all land held in the CRP to a per-acre estimate.

held in sensitive wildlife habitats in our measure of CRP land (only general sign-up and continuous sign-up non-CREP acres are considered here), we do not account for the loss of benefits to wildlife in our estimates. In addition, given that we do not include land held from the Wetlands Reserve Program of CRP into our acreage estimates of CRP, we do not account for the loss of benefits to wetlands in our estimates. Implicitly we assume that the rental payments to these critical CRP lands are large enough to exclude them from consideration of conversion. In addition, given the contention surrounding the use of existence values, we do not consider them here.

Soil erosion has on-site and off-site costs, both of which are generally not accounted for in the market (Poe, 1999). On-site costs of erosion are primarily associated with the long-term impact of soil loss on productivity potential. Excessive erosion diminishes this potential by reducing nutrient supply, water infiltration, and soil water holding capacity, which have economic consequences in terms of lost productivity. Off-site costs of soil erosion and erosion related pollutants are incurred by the public and can be separated into in-stream damages (biological impacts, recreational impacts, water storage damage, navigation, and other preservation values) and off-stream effects (flood damage, sediments in water conveyance, water treatment) (Clark II et al., 1985). We consider each of these dimensions in turn; in the case in which we have identified only one estimate, that is the value that is assumed. Young and Osborn (1990) find an equivalent per acre benefit from gains in soil productivity due to CRP of \$6.69. Ribaudo (1989) finds an equivalent per acre benefit from water storage navigation and flooding of \$3.59, and an equivalent per acre benefit from ditch maintenance, municipal and industrial uses of \$3.68. Goodwin and Smith (2003) find that the CRP has reduced annual soil loss by 1.02 tons per acre from 1982 to 1992. Ribaudo (1986) and Ribaudo (1989) finds widely varying values of off-site damages due to soil erosion, depending on Farm Productivity Region, from \$0.63 to \$7.80 per ton of soil lost. This implies a benefit per acre of CRP land of \$0.64 per acre to \$7.96 per acre. In general, off-site costs of agricultural erosion exceed the on-site costs of erosion by a factor of 2 to 8 (Poe, 1999). This would imply, then, on-site benefits per acre of CRP ranging from \$0.08 to \$3.90 per acre. Given that we are considering land most likely to be converted from CRP held in the Midwest, we use the low estimate for both on and off-site damages of \$0.72 per acre. Summing these four terms together provides the total external soil benefits from land held in the CRP of \$14.68 per acre.

CRP provides external benefits to air quality both in terms of the health benefits of reducing criteria pollutants as well the benefits attained through sequestering carbon. Ribaudo et al. (1990) find an equivalent per acre benefit from reducing health and cleaning costs of \$1.50, which we use as our central estimate of the external benefit of improving air quality.

Finally, summing together the recreational, soil quality and air quality and GHG mitigation benefits of CRP land we have total external benefits of \$47.83 per acre (=31.65+14.68+1.50).

C.9 Calculations Underlying "Implications for Advanced/Cellulosic Renewable Fuel Standards"

The RFS for cellulosic ethanol mandates 60.6 billion liters be blended into the nation's fuel supply by 2002. Assuming perfect complements technology with respect to cellulosic ethanol production, the price of cellulosic ethanol is given by: $P_{CE} = \lambda_{CE,M} P_M + \lambda_{CE,L}$, where P_{CE} is the price of cellulosic ethanol, $\lambda_{CE,M}$ is the amount of biomass feedstock (in dry tons) required per liter of cellulosic ethanol produced (normalized to the wage rate), and $\lambda_{CE,L}$ is the per liter cost of all other (non-feedstock) inputs used in the production of cellulosic ethanol. We note that according to EPA (2010), that $\lambda_{CE,L} = 0.48$ in 2022,[55] Assuming that 322 liters of cellulosic ethanol are produced per dry ton (from Table 5.1) ($\frac{1}{\lambda_{CE,M}}$), we can convert the combined feedstock supply curve for 2022 (see footnote in main text), to an effective cellulosic ethanol supply curve (Perlack and Stokes, 2011), given this price equation. We extrapolate a baseline gasoline price for 2022 from our model's baseline over 2011-2015 of \$0.57 per liter. Given the first order conditions to the fuel blender's problem when cellulosic ethanol is an additional input (in the absence of the RFS on cellulosic ethanol) and this cellulosic ethanol supply curve, we can estimate the supply of cellulosic ethanol implied by the absence of the cellulosic RFS, or 47.7 billion liters. This implies that a binding RFS for cellulosic ethanol will add 12.9 billion liters of ethanol to the economy in 2022. We can repeat these calculations using the 2017 and 2030 supply curves from the Billion Ton Update (Perlack and Stokes, 2011). In this case the amount of cellulosic ethanol added as a result of the RFS for cellulosic ethanol is 28.5 and 0 (non-binding) billion liters, respectively.

The calculation of the cut-off elasticity comes from the observation that the price of blended fuel in the presence of multiple non-petroleum fuels is given by: $P_F = \sum_{c=1}^{C} (P_c - S_c) * \theta_c + \left(1 - \Gamma\left(\sum_{c=1}^{C} \theta_c\right)\right) P_G - t_F$, where the c subscript spans C possible biofuel classes, and θ_c is the share of biofuel in class c per liter of blended fuel. Total differentiating this expression for the case when $dP_F = 0$ for the cellulosic ethanol biofuel class yields the implied cut-off elasticity of cellulosic ethanol supply of 0.19. This calculation assumes a baseline volume of crude oil consumed domestically of 515.745 billion liters (3,285 million barrels) taken from the EIA's 2010 Annual Energy Outlook Reference scenario as reported for light duty vehicles. We also assume a baseline price of gasoline in 2022 of \$0.57 per liter which is extrapolated from the growth rate in the price of gasoline implied across the baseline of our model for the years 2012-2015, and that 18.9 billion liters of advanced (non-cellulosic ethanol, e.g. biodiesel) are already accounted for (consistent with Figure 2.8 in (Perlack and Stokes, 2011)). We can repeat these calculations using the 2017 supply curve from the Billion Ton Update (Perlack and Stokes, 2011). In this case the cut-off elasticity is 0.20.

The portion of the feedstock supply curve for 2022 over which the RFS for cellulosic ethanol is likely to bind corresponds to when the feedstock price ranges from \$49 / dry ton to \$52 / dry ton. Over this portion of the curve the implied cellulosic ethanol supply elasticity is 6.7. The implied elasticities using the 2017 supply curve is 3.8.

To conduct the second part of the analysis, we first compute the life-cycle emissions savings of a composite advanced biofuel, here inclusive of biodiesel, sugarcane ethanol, and cellulosic ethanol from switchgrass and corn residues, relative to their appropriate petroleum substitute (gasoline, except for the case of bidiesel which is diesel).

Our composite advanced biofuel uses the best-case LCA emissions savings for each of these four biofuel classes. For cellulosic ethanol from switchgrass, the biochemical pathway provides the most emissions savings relative to gasoline of -110% (emissions reduction, g

[55] See Table 4.1-26 in EPA (2010).

CO_2e, per mmBTU, Figure 2.6-12 in EPA (2010)). For cellulosic ethanol from corn stover, the biochemical pathway provides the most emissions savings relative to gasoline of -129% (Figure 2.6-12 in EPA (2010)). Figure 2.6-7 in EPA (2010) reports that soybean biodiesel achieves emissions savings relative to diesel of -57%. Sugarcane ethanol that is not sourced from Caribbean Basin Initiative countries and for which residue collection occurs achieves the best emissions savings for sugarcane ethanol relative to gasoline of -91% (Figure 2.6-10). Given an energy content of gasoline of 115,000 BTUs per G, of diesel and biodiesel of 130,000 BTUs per G, and of ethanol of 77,012 BTUs per G, and emissions rates of 98,205 g CO_2e per mmBTUs for gasoline and 97,006 g CO_2e per mmBTUs for diesel, these LCA savings percentages imply emissions savings relative to their petroleum counterpart of -8,319.26, -9,756.22, -6,882.30, and -7,188.14 g CO_2e per G of cellulosic ethanol from switchgrass (biochemical conversion pathway), cellulosic ethanol from corn stover (biochemical conversion pathway), sugarcane ethanol (excluding CBI, with residue collection), and soybean biodiesel, respectively.

Next, we compute the shares of advanced biofuels for each of the four advanced biofuel classes to the total amount of advanced biofuels added by the RFS according to EPA (2010). Table 2.3-1 in EPA (2010) reports that, relative to the AEO reference scenario, that the RFS will add 7.9 billion G of cellulosic ethanol from switchgrass, 4.9 billion G of cellulosic ethanol from corn residue, 1.6 billion G of sugarcane ethanol, and 0.5 billion G of soybean biodiesel in 2022. Of the total 14.9 billion G of advanced biofuels added, this implies shares of each advanced biofuel class of 0.53, 0.33, 0.11, and 0.03, respectively.

To compute the life-cycle emissions savings of a composite advanced biofuel we multiply these shares by the emissions savings of each biofuel class (in g CO_2e per G), and sum across biofuel classes. The result is an LCA emissions savings of -8,599.56 g CO_2e per G of our composite advanced biofuel, which is just the sum of the emissions savings across the four biofuel classes weighted by the share of each biofuel class expected to be added by the RFS in 2022.

Using this, we can compute the best-case expected external benefits from a composite advanced biofuel, were the ethanol quantities added by our simulation of this composite advanced biofuel type and not corn ethanol. Assuming our central estimate for the carbon price, this implies external benefits from GHG emissions of -\$82.70, -\$128.02, and -\$194.76 million when the VEETC is renewed, in 2011, 2013, and 2015, respectively. When the VEETC is allowed to expire, these values are -\$78.69, -\$124.10, and -\$193.96 million in 2011, 2013, and 2015, respectively.

C.10 Additional Results

The full results for the case when the VEETC is allowed to expire when the RFS is imposed are also provided here. Table C.14 reports the impact of the of the mandate on ethanol consumption. Table C.15 provides the impact of the RFS on land markets. Table C.15 presents the impact of the RFS on fuel markets and vehicle miles travelled. Table C.18 decomposes net costs according to the marginal welfare formula presented in (3.3.24). Table C.19 reports a benefit-cost assessment of the RFS. Table C.16 reports the crop prices, crude oil prices, and import and export quantities used to compute the change in the trade balance due to the RFS.

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Table C.1: Key Elasticity Values

	Central Value
Key Elasticities	
Blended Fuel Demand	-0.34
Food Demand	-0.12
Corn Supply (area)	0.29
Other Crops Supply wrt to Corn Price	-0.12
CRP wrt to Net Returns to Cropland	-0.07
Corn Export Demand	-0.65
Other Crops Export Demand	-0.59
Crude Oil Excess Supply	0.5

Table C.2: External Benefit Parameters

Model Parameter	Low	Central	High	Source
External Benefit from Greenhouse Gas Emissions				
External Damages from GHG Emissions MD^{GHG} (\$/ton Ce)	\$0.70	\$25.00	\$100.00	Parry and Small (2005)
Oil Dependency Related External Benefits, MEC^{P}	\$0.10	\$0.22	\$0.59	
Oil Price Volatility (\$/gallon gasoline)	\$0.00	\$0.03	\$0.20	Parry et al. (2007)
Market Power (\$/gallon gasoline)	\$0.07	\$0.10	\$0.24	Parry et al. (2007)
Military and Geopolitical Costs (\$/gallon gasoline)	\$0.03	\$0.09	\$0.15	Delucchi and Murphy (2008)
VMT Market External Benefits				
Local Air Pollution, MD^{M}_{LP} (\$/mile)	\$0.0040	\$0.0100	\$0.1000	Small and Verhoef (2007) and Parry and Small (2005)
Accidents, MD^{M}_{A} (\$/mile)	\$0.0140	\$0.0350	\$0.0875	Parry et al. (2010) and Parry and Small (2005)
Congestion, MD^{M}_{C} (\$/mile)	\$0.0150	\$0.0350	\$0.0900	Parry and Small (2005)
Land Use External Benefits				
Total External Benefits from CRP, MEB^{N} (\$/acre) *	\$11.96	\$47.83	\$83.70	Multiple sources.

Notes: *: Is the sum of \$10.02/acre for benefits from wildlife viewing, \$20.56/acre for benefits from hunting, \$1.07/acre for benefits from water quality improvements,\$14.68/acre for benefits from soil quality improvements, and \$1.50/acre for additional air quality improvements. See Appendix, Section C.8 for full discussion.

Table C.3: Description of US Economy in Year of Calibration - 2003

	Value	Source
Total Size of Economy (billion $)	$7,667.60	NIPA
Net Government Expenditures (billion $)	$2,828.90	NIPA
After Tax Value of Labor (billion $)	$4,811.08	
Net Returns from Land Endowment (billion $)	$27.61	NASS, CRPS, CCR
US Land Endowment (million hectares)	112.68	
Corn	31.37	NASS
Soybeans	29.33	NASS
Wheat	21.47	NASS
Hay	25.65	NASS
Cotton	4.68	NASS
CRP	13.57	CRPS
Crop Yields (metric ton/hectare)		
Corn	8.9	NASS
Soybeans	2.6	NASS
Wheat	3.0	NASS
Hay	6.1	NASS
Cotton	0.8	NASS
Crop Prices ($/metric ton)		
Corn	$95.23	NASS
Soybeans	$269.62	NASS
Hay	$94.22	NASS
Wheat	$118.65	NASS
Cotton	$1,036.32	NASS
Fuel Quantities		
VMT (trillion passenger miles)	2.69	FHWA
Blended Fuel (billion liters)	497.21	
Ethanol (billion liters)	10.39	FHWA
Regular Gasoline (billion liters)	490.28	FHWA
Domestic Crude Oil (billion barrels)	2.34	GCH, CSD, BNI
Fuel Prices		
VMT ($/passenger mile)	$0.19	
Blended Fuel ($/liter)	$0.41	
Ethanol ($/liter)	$0.35	
Regular Gasoline ($/liter)	$0.23	AER
Crude Oil ($/liter)	$0.18	AER
Labor Tax Rate (%)	36.59%	
Fuel Tax ($/liter)	$0.10	FHWA
CRP Rental Payment ($/hectare)	$114.48	CRPS
Price of Labor ($/hour)	$9.05	NASS

Notes: Entries with no source listed are imputed given other data and calibration assumptions.

Table C.4: Key Parameter Values

Parameter	Value	Source
Households		
Elasticity of substitution, Household Utility, σ_U	0.5	See Text
Elasticity of substitution, Household Utility, σ_T	0.09	See Text
Elasticity of substitution, VMT, σ_M	0.21	See Text
Ratio of fuel cost to total cost of driving	0.4	See Text
Initial Fuel Economy (km/liter)	8.7	FHWA
Ethanol		
kilograms corn required per liter ethanol, λ_{E,Y_1}	2.56	(Wang, 2009)
Labor expenditures per liter ethanol	$0.13	(Farrell et al., 2006)
Regular Gasoline and Crude Oil		
Elasticity of substitution, Regular Gasoline Production, σ_P	0.06	See Text
Share of per unit crude oil cost to total cost of gasoline	0.61	GCH, CSD, BNI
Own price elasticity of crude oil supply	0.50	See Text
Crude oil yield for regular gasoline	0.47	GCH, CSD, BNI

Notes: See text for acronym definitions. Values are reported for 2003. A subset of parameters are updated annually, see text for details.

Table C.5: Targeted Crop Area Elasticities

	Corn Area	Soybean Area	Hay Area	Wheat Area	Cotton Area
Corn Price	0.29	-0.23	-0.05	-0.05	-0.07
Soybean Price	-0.15	0.27	-0.01	-0.01	-0.08
Hay Price	-0.07	-0.01	0.20	-0.08	-0.10
Wheat Price	-0.07	-0.01	-0.06	0.34	-0.06
Cotton Price	-0.03	-0.02	-0.08	-0.01	0.47

Notes: The elasticity of CRP land with respect to the marginal net returns to cropland is -0.07. The own price elasticity of hay area, the cross price elasticity of hay area with respect to the price of corn and the elasticity of corn area with respect to the price of hay represent an average of Arnade and Kelch (2007) and Orazem and Miranowski (1994). The elasticity of hay area with respect to the price soybeans, wheat and cotton, and the elasticity of wheat and cotton area with respect to the price of hay represent best guesses. All remaining values are from Lin et al. (2000).

Table C.6: Agricultural Expenditure Dataset

Total Expenditures ($/hectare)

	Labor	Capital	Energy	Fertilizer	Total
Corn	73.32	142.06	57.06	386.97	659.41
Soybeans	44.50	108.33	21.67	209.92	384.43
Hay	49.08	130.13	27.06	153.26	359.52
Wheat	49.08	130.13	27.06	167.96	374.22
Cotton	124.39	157.14	60.27	749.58	1092.37

Components of Fertilizer Expenditure ($/hectare)

	N	P	K	Seed	Chemicals	Other
Corn	89.97	21.40	19.05	84.76	64.74	107.05
Soybeans	2.52	5.41	7.78	67.76	41.81	84.63
Hay	20.11	15.20	7.69	18.78	17.15	74.31
Wheat	43.89	11.27	2.59	18.78	17.15	74.31
Cotton	52.19	13.57	13.49	91.90	162.62	415.83

Table C.7: Additional Calibration Parameters

Model Parameter	Value	Source
Households		
Expenditure Share on Food	0.035	
Expenditure Share on VMT	0.065	
Crop Export Markets		
Elasticity of ROW demand for US corn exports	-0.65	
Share of corn exports to Total US Production	0.19	PSD
Elasticity of ROW demand for US soybean exports	-0.6	
Share of soybean exports to Total US Production	0.36	PSD
Elasticity of ROW demand for US wheat exports	-0.55	
Share of wheat exports to Total US Production	0.49	PSD
Elasticity of ROW demand for US cotton exports	-0.75	
Share of cotton exports to Total US Production	1	PSD
Ethanol		
Average tariff rate (plus fuel surcharge) per liter of ethanol	$0.02	
Gasoline and Crude Oil		
Share of crude oil cost to total cost of gasoline per liter	0.61	EIA
Crude oil yield for gasoline	0.47	EIA
Other Markets		
Elasticity of substitution, Food Production, σ_{X1}	0.08	
Elasticity of substitution, Food Production, σ_{X2}	0.3	
Elasticity of substitution, Food Production, σ_{X3}	0.25	
Share of crop expenditures on food to total food expenditures	0.19	

Table C.8: Final Product/Activity Emissions Factors

	Central	Low	High	Source
Gasoline ($kgCO_2e$/liter)	3.0			
Combustion	2.4	-	-	EPA (2010)
Production	0.6	-	-	EPA (2010)
Ethanol ($kgCO_2e$/liter)				
Combustion	0.02	-	-	EPA (2010)
Production	0.6	-	-	EPA (2010)
Crude Oil ($kgCO_2e$/liter)	2.6	-	-	EPA (2011)
Agriculture ($mgCO_2e$/ha/year)				
Corn	3.2	2.9	5.6	
Soybeans	0.5	1.8	0.4	
Hay	1.3	1.3	2.5	
Wheat	1.0	1.6	1.3	
Cotton	1.4	1.6	2.9	
Land Use Emissions Benefits Lost Upon Conversion ($mgCO_2e$/ha/year)				
CRP	2.3	1.1	4.6	Fargione et al. (2008)
Rest of World	8.0	5.9	10.5	EPA (2010)

Notes: See Appendix for description of calculations. N_2O emissions from agricultural production depend on crop yields and therefore vary by year and policy. Values in baseline for 2003 are reported here. The emissions factor for crude oil is the average emissions from gasoline and distillates used outside the US, weighted by 2003 quantities of these products.

Table C.9: Comparison of Model Predictions to Historic Data

	2003	2004-2009, Avg.
Land Harvested (million hectares)		
Corn, Our Prediction	31.38	33.14
Corn, USDA	31.38	33.74
% Difference	0.00%	-1.78%
Soybeans, Our Prediction	29.33	29.18
Soybeans, USDA	29.33	29.34
% Difference	0.00%	-0.56%
Hay, Our Prediction	25.65	26.07
Hay, USDA	25.64	24.63
% Difference	0.02%	5.88%
Wheat, Our Prediction	21.47	20.69
Wheat, USDA	21.47	20.46
% Difference	0.00%	1.08 %
Cotton, Our Prediction	4.86	3.76
Cotton, USDA	4.86	4.41
% Difference	-0.01%	-14.75%
CRP, Our Prediction	13.57	13.41
CRP, USDA	13.57	13.61
% Difference	0.00%	-1.50%
Ethanol Quantities (billion liters)		
Ethanol Baseline Quantities	10.4	27.6
Total US Demand, RFA	10.4	25.4
% Difference	0.00%	8.62%

Notes: USDA value for corn includes total harvested for silage and for grain.

Table C.10: Comparison of Model Predictions to Average of 2006-2009 USDA Long-Term Projections

	2010	2012	2015
Harvested Land (million hectares)			
Corn Acres, Our Baseline Estimate	33.86	33.90	33.38
Corn Acres, Our Post-RFS Estimate	34.27	34.98	35.33
Corn Acres, Avg. 2006-2009 LT Proj.*	32.67	33.18	33.07
% Difference, Baseline	3.65%	2.18%	0.93%
% Difference, Post-RFS	4.91%	5.45%	6.83%
Soybean Acres, Our Baseline Estimate	29.08	29.38	29.44
Soybean Acres, Our Post-RFS Estimate	28.97	29.05	28.87
Soybean Acres, Avg. 2006-2009 LT Proj.	28.37	28.00	27.75
% Difference, Baseline	2.51%	4.94%	6.10%
% Difference, Post-RFS	2.13%	3.77%	4.04%
Wheat Acres, Our Baseline Estimate	20.70	20.57	22.44
Wheat Acres, Our Post-RFS Estimate	20.62	20.30	22.08
Wheat Acres, Avg. 2006-2009 LT Proj.	20.35	20.17	20.03
% Difference, Baseline	1.74%	1.97%	12.02%
% Difference, Post-RFS	1.34%	0.61%	10.23%
Cotton Acres, Our Baseline Estimate	3.75	3.72	3.77
Cotton Acres, Our Post-RFS Estimate	3.69	3.57	3.48
Cotton Acres, Avg. 2006-2009 LT Proj.	4.40	4.51	4.56
% Difference, Baseline	-14.86%	-17.61%	-17.37%
% Difference, Post-RFS	-16.23%	-21.00%	-23.83%

Ethanol (billion liters)			
Ethanol, Our Baseline Estimate	41.79	43.94	45.44
Ethanol, Avg. 2006-2009 LT Proj.**	38.31	40.47	43.23
% Difference	-8.29%	-7.92%	4.94%

Notes: *: Does not include corn land harvested for silage, since silage is not tracked by USDA L-T Projections. **: Figure for 2012 and 2015 takes corn for ethanol and converts to ethanol using conversion parameters from our model for the given year. Figure for 2009 comes from the RFA and represents total US demand for ethanol. ***: Estimate computed is based on a per gallon of blended fuel share mandate on ethanol consumption, which is calculated annually by taking the RFV statutory quantities and dividing by the expected blended fuel consumption (post-policy) for a given year.

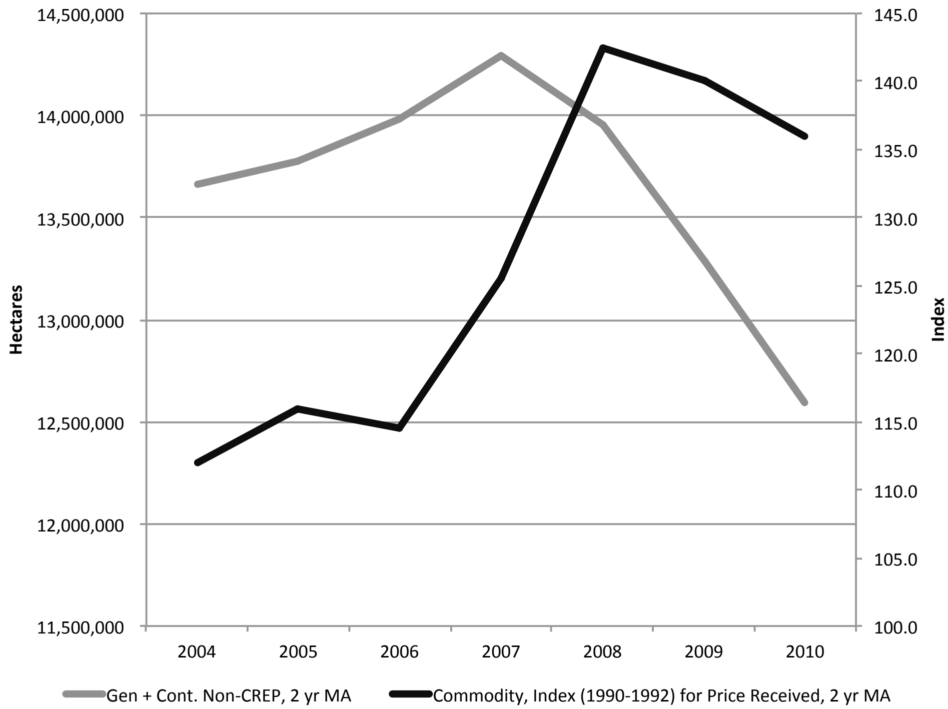

Figure C.1: CRP Acres Against Commodity Price Index (Price Received)

Table C.11: Change in CRP For Years 2003-2010 (Million hectares)

Year	General	Cont. Non-CREP	Total	Annual Change	% Annual Change
2003	12.80	0.77	13.57		
2004	12.88	0.88	13.76	0.19	1.43%
2005	12.84	0.96	13.80	0.04	0.28%
2006	13.13	1.04	14.17	0.37	2.70%
2007	13.32	1.10	14.42	0.25	1.78%
2008	12.36	1.12	13.48	-0.94	-6.52%
2009	11.90	1.20	13.10	-0.38	-2.84%
2010	10.79	1.30	12.09	-1.01	-7.73%

Notes: Data taken from *Conservation Reserve Program Annual Summary and Enrollment Statistics* for years 2003 through 2010.

Table C.12: Calibration of Crude Oil Market

Crude Market Component	Quantity (billion liters)	Ratio with Crude for US Gasoline	Central Elasticity
Total World Crude Oil	4545.8	-	-
US Demand for Crude Oil for Gasoline	490.3	-	0.50
US Crude Oil Supply	499.6	1.0	0.045
ROW Crude Oil Supply	4046.2	8.3	0.035
ROW Crude Oil Demand	3419.5	7.0	-0.02
US Distillate Demand	225.0	0.5	-0.02
US Other Crude Products Demand	411.0	0.8	-0.02

Notes: The value for crude for US gasoline is the value used in our model. This value is slightly below the total quantity of crude for US gasoline reported by the EIA because we ignore US gasoline for non-transportation purposes in our model. The elasticity of crude for US gasoline is calculated following equation (B.3.2). All other elasticity values are from literature sources reported in the text. Our category of other crude products includes residual fuels, jet fuel, kerosene, LPG and EIA defined other petroleum products.

Table C.13: Impact of the RFS on Export and Import Markets

	2011	2013	2015
Price of Corn ($/bu), Baseline	3.18	3.24	3.47
% Change in Price of Corn	8.1 %	16.6 %	25.2 %
Price of Soybeans ($/bu), Baseline	8.16	8.28	9.03
% Change in Price of Soybeans	1.0 %	1.3 %	3.0 %
Price of Wheat ($/bu), Baseline	4.33	4.36	3.64
% Change in Price of Wheat	4.2 %	8.7 %	20.0 %
Price of Crude Oil ($/bbl), Baseline	67.71	70.40	78.11
% Change in Price of Crude Oil	-0.9 %	-1.4 %	-2.2 %
Corn Exports (billion bu)	1.92	1.95	1.92
% Change in Corn Exports	-4.4 %	-8.3 %	-11.5 %
Soybean Exports (billion bu)	1.20	1.26	1.29
% Change in Soybean Exports	-0.5 %	-0.6 %	-1.2 %
Wheat Exports (billion bu)	1.00	1.00	1.11
% Change in Wheat Exports	-2.2 %	-4.4 %	-9.3 %
Crude Oil Imports (billion bbls)	3.06	3.08	3.07
% Change in Crude Oil Imports	-0.4 %	-0.6 %	-0.9 %

Table C.14: Corn-based Ethanol Renewable Fuel Standard (RFS): Baseline and Mandated Quantities Over Time, VEETC Swapped

	2003	2008	2009	2010	2011	2012	2013	2014	2015
Corn-based Ethanol Baseline (billion G)	2.7	10.0	10.7	11.3	11.5	11.8	12.0	12.1	12.1
Mandated Quantities*	-	9.0	10.5	12.2	12.8	13.4	13.9	14.5	15.1
Difference Between Mandated and Baseline	-	-	-	0.9	1.2	1.5	1.9	2.5	3.0
% Difference in Estimated Mandate Relative to Baseline	-	-	-	6.5%	9.3%	11.6%	14.9%	19.6%	23.9%
Does the RFS Bind?**	-	No	No	Yes	Yes	Yes	Yes	Yes	Yes

Notes: *: Estimate computed is based on a per gallon of blended fuel share mandate on ethanol consumption, which is calculated annually by taking the RFS statutory quantities and dividing by the expected blended fuel consumption (post-policy) for a given year. **: If the estimated RFS quantity is lower than what would have been produced in the absence of the policy (e.g. the baseline), then the RFS does not bind.

Table C.15: Effects of the Corn-based Ethanol RFS on Land-Use, VEETC Swapped

	2011	2013	2015
Baseline Corn (million acres)	84.0	84.0	82.6
% Change in Corn Acres Due to RFS	1.9%	4.1%	5.8%
Due to Intra-Cropland Substitution*	1.4%	3.1%	4.5%
Due to Adjustment in CRP	0.5%	1.0%	1.2%
Change in CRP (acres) Per Equivalent Gallon of Gasoline of Ethanol Mandated**	-0.001	-0.001	-0.001

Notes: All acres reported are harvested acres. *: Change in corn acres due to intra-cropland substitution reflects the reductions in soybean, wheat, hay, and cotton acres due to the RFS. **: An equivalent gallon of gasoline (EGG) is the energy-content adjusted volume of ethanol or blended fuel relative to the energy content of gasoline. Per EGG of ethanol mandated denotes normalization by the amount of ethanol added by the RFS.

Table C.16: Impact of RFS on Export and Import Markets, VEETC Swapped

	2011	2013	2015
Price of Corn ($/bu), Baseline	3.18	3.24	3.47
% Change in Price of Corn	8.6%	17.0%	25.6%
Price of Soybeans ($/bu), Baseline	8.16	8.28	9.03
% Change in Price of Soybeans	0.8%	1.0%	2.7%
Price of Wheat ($/bu), Baseline	4.33	4.36	3.64
% Change in Price of Wheat	3.9%	8.4%	19.7%
Price of Cotton ($/lb), Baseline	0.63	0.65	0.65
% Change in Price of Cotton	-2.2%	-6.1%	1.0%
Price of Crude Oil ($/bbl), Baseline	67.71	70.40	78.11
% Change in Price of Crude Oil	-2.8%	-3.4%	-3.9%

Corn Exports (billion bu)	1.92	1.95	1.92
% Change in Corn Exports	-4.7%	-8.5%	-11.7%
Soybean Exports (billion bu)	1.20	1.26	1.29
% Change in Soybean Exports	-0.4%	-0.5%	-1.1%
Wheat Exports (billion bu)	1.00	1.00	1.11
% Change in Wheat Exports	-2.1%	-4.2%	-9.2%
Cotton Exports (billion lbs)	5.50	5.61	5.85
% Change in Cotton Exports	1.4%	3.9%	-0.6%
Crude Oil Imports (billion bbls)	3.06	3.08	3.07
% Change in Crude Oil Imports	-1.1%	-1.3%	-1.6%

Table C.17: Effects of the Corn-based Ethanol RFS on Fuel Markets and VMT, VEETC Swapped

	2011	2013	2015
Baseline Price of Blended Fuel (in $/Equivalent Gallon of Gasoline)*	$2.27	$2.32	$2.45
% Change	0.9%	1.0%	1.0%
% Due to the Increase in the Price of Ethanol	2.8%	3.6%	4.6%
% Due to the Decrease in the Price of Gasoline	-1.9%	-2.6%	-3.6%
Baseline Ethanol (Billion Equivalent Gallons Gasoline)	7.9	8.1	8.1
% Change in Ethanol Due to RFS	10.9%	16.4%	25.1%
Corresponding to Displaced Gasoline	18.8%	24.3%	32.2%
Corresponding to Additional Blended Fuel	-7.9%	-7.9%	-7.1%
Gallons of Gasoline Displaced Per EGG of Ethanol Mandated	1.72	1.48	1.28
EGG of Blended Fuel Added Per EGG of Ethanol Mandated	-0.72	-0.48	-0.28
Baseline Price of Miles (in $/mile)	$0.22	$0.22	$0.22
% Change	0.5%	0.6%	0.6%
Change in VMT (miles) Per EGG of Ethanol Mandated	-12.10	-8.30	-5.12

Notes: *: An equivalent gallon of gasoline (EGG) is the energy-content adjusted volume of ethanol or blended fuel relative to the energy content of gasoline. Per EGG of ethanol mandated denotes normalization by the amount of ethanol added by the RFS. The prices of blended fuel and miles are inclusive of the VEETC and the fuel tax.

Table C.18: The Welfare Consequences of the RFS for Conventional Biofuels, VEETC Swapped

	2011	2013	2015
Net Costs Due to RFS (million $)	308.7	392.1	391.3
Net Costs, Including Change in Trade Balance	-6,224.7	-8,431.1	-11,848.0
dW^{PC}, *Primary Cost*	1,629.4	2,171.9	2,837.7
dW^{E}, *Subsidy Interaction Effect*	-547.9	-864.0	-1,350.5
dW^{F}, *Blended Fuel Output Effect*	-449.7	-487.2	-525.6
External Damages from Mileage Related Externalities	-880.6	-931.5	-883.8
From Local Air Pollution	-207.2	-219.2	-208.0
From Accidents	-310.8	-328.8	-311.9
From Congestion	-362.6	-383.6	-363.9
External Benefits from GHG Emissions	-43.6	-21.8	-9.7
Fuel Tax Costs	474.5	466.1	367.9
dW^{P}, *Oil Premium Effect**	-324.4	-430.3	-571.7
dW^{N}, *CRP Interaction Effect*	1.2	1.7	1.4
CRP Related Externalities**	24.1	47.7	62.5
Reduction in CRP Rental Payments	-22.8	-45.9	-61.1
dW^{B}, *Change in Terms of Trade*	-6,533.4	-8,823.3	-12,239.3

Notes: *: Benefits included in this category include the per gallon benefits from reduced military and geopolitical related expenditures, reduced crude oil price volatility, and reduced market power. **: External benefits to CRP land include benefits from wildlife (hunting and viewing), non-GHG air quality improvements, soil quality improvements, and recreation use benefits.

Table C.19: Benefit-Cost Analysis of the RFS for Conventional Biofuels, VEETC Swapped

	2011	2013	2015
Change in Ethanol Due to RFS (Billion Equivalent Gallons of Gasoline)*	4.4	4.8	4.9
Excluding Change in Trade Balance			
Net Costs (in million $)	308.7	392.1	391.3
Gross Costs	2,128.0	2,685.7	3,268.1
Gross Benefits	-1,819.3	-2,293.6	-2,876.8
Net Costs Per EGG of Ethanol Mandated ($ per EGG)	0.36	0.30	0.19
Net Costs Per EGG of Displaced Gasoline ($ per EGG)	0.21	0.20	0.15
Ratio of Gross Benefits to Gross Costs	0.85	0.85	0.88
Freq. By Which Gross Benefits Exceed Gross Costs**	27.3%	25.0%	26.0%
Including Change in Trade Balance			
Net Costs (million $)	-6,224.7	-8,431.1	-11,848.0
Gross Costs	2,128.0	2,685.7	3,268.1
Gross Benefits	-8,352.7	-11,116.9	-15,116.0
Net Costs Per EGG of Ethanol Mandated ($ per EGG)	-7.27	-6.38	-5.83
Net Costs Per EGG of Displaced Gasoline ($ per EGG)	-4.19	-4.28	-4.54
Ratio of Gross Benefits to Gross Costs	3.93	4.14	4.63
Freq. By Which Gross Benefits Exceed Gross Costs**	100.0%	100.0%	100.0%

Notes: *: An equivalent gallon of gasoline (EGG) is the energy-content adjusted volume of ethanol or blended fuel relative to the energy content of gasoline. Per EGG of ethanol mandated denotes normalization by the amount of ethanol added by the RFS. Per EGG of displaced gasoline denotes normalization by the amount of gasoline displaced by the RFS. **: Reflects the frequency by which gross benefits exceed costs across 2,000 Monte Carlo random draws of the vector of external benefits. See Appendix, Section C.8 for additional details. All other values reflect our central parameter estimates.